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Post Docket: 40- 6563

March 24, 2006

Mr. Amir Kouhestani
US Nuclear Regulatory Commission
2 White Flint North
11545 Rockville Pike
Rockville MD 20852 - 2738

RE: NRC Docket 40-06563, NRC License STB - 401

Dear Mr. Kouhestani:

Mallinckrodt's responses to certain NRC staff requests for information concerning the Draft C-T Phase II Decommissioning Plan (CT Phase II DP) are enclosed. These responses are a follow-up to discussions between Mallinckrodt and NRC staff on January 24, 2006. This meeting was summarized in the NRC report, dated February 16, 2006, and these responses relate specifically to Actions 2, 4, and 5. Enclosed are five copies of the following:

- revised CT Phase II DP, §5, Dose Modeling
- revised CT Phase II DP, Appendix C, describing derivation of DCGL in soil
- clarification in CT Phase II DP, §14 Facility Radiation Surveys, specifically about final status surveys
- response to NRC RAI 4
- response to NRC RAI 41
- response to NRC RAI 43
- response to NRC RAI 44
- response to NRC RAI 48
- response to NRC RAI 49, and
- response to NRC RAI 51

Regarding Action "1," it always has been, as most recently discussed during our meeting held on October 5, 2005, that Mallinckrodt has always intended to determine an appropriate delineation of contaminated areas between the MED-AEC activities versus the NRC-licensed contaminated areas. Mallinckrodt has had multiple meetings with the USACE regarding delineation of the URO burials reflected in the C-T Decommissioning Plan. The vertical and lateral extent of the boundaries of the URO burials has been discussed with

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USACE. There have been many discussions and transfers of information, but meetings to specifically discuss URO delineation were held with the USACE in September, October, and November of 2002, and February, April, August and December of 2003. As you are aware, Mallinckrodt presented a proposal to USACE on August 8, 2003, and is waiting for a response concerning this issue. USACE has stated a response is being prepared.

Nevertheless, realizing that the timing of the settlement with the USACE might not match exactly with the development of DP, Mallinckrodt stated in the second paragraph of the Decommissioning Goals of the DP plan on page 1-2 that:

> *Delineation of responsibility for remediation, particularly in areas known as Plants 6 and 7 within the St. Louis Plant site, remains to be decided between Mallinckrodt and the U.S. Army Corps of Engineers. Mallinckrodt intends that its responsibility for any C-T residue remediation in those areas in question, aside from wastewater basins, will be addressed in a separate license amendment request to remove that source material.*

If necessary, Mallinckrodt remains willing to move forward with the remediation of the area known as Plant 5 while the delineation of areas in Plants 6 and 7 will be completed after final negotiations of the delineation.

Additionally, Mallinckrodt has had several discussions with NRC concerning the development of DCGLs for the site. NRC suggested that Mallinckrodt might consider the dose modeling approach as an alternative to the DCGL approach. After meeting with NRC staff last year, Mallinckrodt stated it preferred to revise responses to related RAIs because Mallinckrodt thought it possible to resolve NRC staff questions. Mallinckrodt presented and discussed revised responses with NRC staff at the January 24th meeting. Mallinckrodt is hopeful that NRC staff will accept the revised responses. If Mallinckrodt cannot resolve the issues raised by NRC staff concerning DCGLs, Mallinckrodt may consider adopting the dose modeling approach as suggested in order to move the process forward.

If you have any further questions concerning the C-T Phase II Decommissioning Plan or concerning these responses, please contact me at 314-654-6393.

Sincerely yours,

James K. Grant
Director, Environmental Remediation

Enc.:

Post Docket: 40-6563

5. DOSE MODELING

5.1. INTRODUCTION

Radiological dose criteria for decommissioning lands and structures[1] provide the basis of determining maximum acceptable residual radionuclide concentration for remediation of residual radioactivity at nuclear facilities undergoing decommissioning. These criteria determine the extent to which lands and structures must be remediated before decommissioning of a site can be considered complete and the license terminated. This chapter describes the derivation of soil concentration guideline levels, $DCGL_W$ [2] and $DCGL_{EMC}$ [3], for land affected by C-T process operation and areal contamination guideline levels for surficial contamination on pavement affected by C-T process operation. Criteria for buildings and structures were derived in the C-T Phase I Decommissioning Plan (Phase I Plan).

To help decide what actions are reasonable to mitigate potential exposure to residual radionuclides in soil and to assure the radiological dose limit is met, maximum acceptable levels of residual radioactivity concentration in soil must be derived for soil remaining after decommissioning. To do this one must estimate the quantitative relation between radionuclide concentration in the soil and potential radiation dose to an average person in the group who might be exposed the most to residual radionuclides in land in Plant 5. Radiological dose modeling by mathematical simulation is a way to describe this source-to-dose relation, thereby enabling one to derive maximum acceptable radionuclide concentration to guide decommissioning and/or decide compliance with the decommissioning regulation. Dose modeling involves:

1. the radioactive source term;
2. an exposure scenario considering the site environment and pathways of exposure;
3. relation of the source term and potential radiological dose; and
4. parameters in the model.

<u>Assessment Methodology</u>. An objective of an environmental exposure pathway analysis is to derive a maximum acceptable average concentration of residual, licensed radioactive material ($DCGL_W$) that will assure conformance with regulatory limit(s) on radiological dose. To derive a $DCGL_W$, one describes land use scenarios based on anticipated site conditions and uses. For each land use scenario, reasonably anticipated environmental radionuclide exposure pathways are described. A mathematical model with simplified representations of site physical conditions and the potentially maximally exposed group of people is used to calculate future exposures and radiation doses as a function of time and concentration of nuclides in the soil. The relationship between dose and radionuclide concentration in soil is computed with the mathematical model.

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[1] 10 CFR Part 20, subpart E

[2] $DCGL_W$ = derived concentration guideline level corresponding to the release criterion for the nonparametric statistical test. ref. MARSSIM.

[3] $DCGL_{EMC}$ = derived concentration guideline level corresponding to the acceptance criterion for elevated measurements comparison ref. MARSSIM.

Reasonable remediation alternatives are posed to clean the site to comply with the DCGL.

Under NRC regulation for decommissioning, pathway analysis includes the estimation of radiation doses that might be received by a typical member of a small group of people from future uses of the site as much as 1,000 years into the future. Thus, this analysis considers not only the current conditions at the site, but projected conditions as well. The analysis evaluates potential uses of the site and potential migration of radioactive materials through the environment over time, accounting for both natural processes and human activities that could be expected to alter the patterns or rates of contaminant movement. The primary objectives of the environmental radiation exposure analysis is to derive the concentration of uranium series and thorium series radionuclides in soil in Plant 5 that potentially produce a 25 mrem/yr radiological dose equivalent above background to an average member of the critical group.

5.2. SOURCE TERM

Residual radioactive sources from C-T processing are the thorium series, the uranium series, and the actinium (U^{235}) series. The thorium decay series may be assumed to be in secular radioactive equilibrium because Th^{232} progeny are relatively short-lived. U^{238} and U^{235} are presumed to be present at the ratio present in natural uranium ore.

The existing distributions of residual source material in soil and on pavement in Plant 5 are described in Section 4 of the C-T Phase II Decommissioning Plan (Phase II Plan). A remediation goal is that radioactivity concentrations exceeding the DCGL will be removed.

By deriving nuclide-specific concentration limits equivalent to the dose limit, *i.e.*, DCGL, and by removing soil containing more radioactivity than the DCGL, acceptable spatial variability of any remaining radioactive residue will be achieved by remedial action and confirmed by a final radiation status survey. This provides the best assurance before the fact that acceptable spatial variability of radioactive residue will be achieved.

5.3. LAND USE SCENARIO

Mallinckrodt's site is in an urban industrial area. Manufacturing and support buildings cover a large portion of the site, and the remainder of the area is typically paved with asphalt or concrete. Mallinckrodt has owned the site and has operated chemical manufacturing facilities on the site since 1867. It intends to continue industrial use of the site, including Plant 5 where C-T facilities are being decommissioned.

The site is in an area whose zoning by the City of St. Louis allows all uses except new or converted dwellings. Some uses allowed within this zone under conditional use permit are acid manufacture, petroleum refining, and stockyards.[4] Land use within a 1.6 km (1-mi) radius of the site reflects a mixture of commercial, industrial, and residential uses. The closest residential

4 St. Louis City Revised Code, Chapter 26.60, K UNRESTRICTED DISTRICT

dwelling is located on North Broadway, approximately 60 m (200 ft) south of the site.[5] The long-term plans for this area are to retain the industrial uses, encourage the wholesale produce district, and phase out any junkyards, truck storage lots, and the remaining marginal residential uses.

The foreseeable use of Mallinckrodt's St. Louis downtown site where C-T facilities are being decommissioned is for continued industrial or commercial use. This is reasonably assured without additional restrictions. Residential use is not expected because of historical and current land use and because of government land use zoning. Agricultural usage is not expected or likely because of the poor soil quality and the prevailing land use in the area.

5.4. CRITICAL GROUP

As a result of the land use scenario, workers are potentially subject to the most exposure in the future. Mallinckrodt limits access to its facilities to employees, subcontracting construction workers, and authorized visitors and maintains 24-hour security at the property. Labor laws prohibit employment of minors. The maximum exposure could occur in to a typical industrial worker who spends most of their time in a building and some time out-of-doors.

Radioactive contamination on interior and exterior surfaces of the buildings has been addressed in the Phase I Plan. The regulated sources of radiation exposure in the Phase II Plan would be in soil and or on pavement in Plant 5. An industrial work scenario involves employees who spend most of their time in a building and some time out-of-doors. This critical group could potentially be exposed to outdoor sources by direct irradiation, by ingestion of soil, and by inhalation of airborne dust. While indoors, they could be exposed to radiation penetrating the floor of a building or to airborne dust that enters the building.

5.5. ENVIRONMENTAL EXPOSURE PATHWAYS

Whereas decommissioning criteria for buildings was addressed in the C-T Phase I Plan, the Phase II Plan addresses decommissioning criteria for soil, pavement, and building slabs. Thus, environmental pathways from residual source material in soil or on surfaces of pavement or building slabs to potential exposure of people in the critical group of workers are of interest to derivation of DCGL.

5.5.1. Pathways to Industrial Worker

A typical industrial worker will spend most of their time in a building and some time out-of-doors. Such an *industrial worker* might be exposed to radionuclides in soil or on the surface of pavement or a building slab in the following ways.

1. Gamma radiation emitted by contaminated soil might irradiate a worker directly while out-of-doors.

[5] Feasibility Study for the St. Louis Downtown Site, St. Louis, Missouri, U.S. Army Corps of Engineers, St. Louis District, Formerly Utilized Sites Remedial Action Program, April 1998, page 2-4.

2. Contaminated soil might be suspended as airborne dust and inhaled by a worker while out-of doors.
3. Contaminated soil might get on a worker's clothing and/or hands and be eaten inadvertently.
4. Gamma radiation emitted by contaminated soil might penetrate the floor and or walls of a building and irradiate a worker while indoors.
5. Contaminated soil might be suspended as airborne dust; some fraction of that dust might enter a building in ventilation air, and be inhaled by a worker while inside a building.

Although credit was not taken in dose modeling to derive DCGL for contaminated soil, a mitigating factor is that pavement shields an industrial worker from some direct radiation from soil and from creation of airborne dust from soil beneath the pavement. Most of Plant 5 is covered by buildings or is paved with concrete or macadam. Characterization surveys have identified some radioactivity on pavement that is elevated above expected background. As a practical matter, a worker would not be exposed simultaneously to bare ground and to pavement. Thus, separately an industrial worker might be exposed by:

- direct irradiation by the surficial source while out-of-doors;
- inhalation of dust suspended from the surface while out-of-doors;
- ingestion of dust;
- direct irradiation while indoors; and
- inhalation while indoors of dust suspended from a surficial source.

5.5.2. Pathways Not Present

5.5.2.1. Surface Water.[6]

Site wastewater, storm water, and all other surface drainage flow via site sewers and drains to a combined municipal sewer system and then to the Metropolitan St. Louis Sewer District (MSD) Bissell Point Treatment Plant. The Bissell Point Plant is located approximately 1 km (0.7 mi.) north (upstream) of the site. Treated water is discharged to the Mississippi River. During storm periods, the combined sewer system serving the site is diverted directly to the Mississippi River. There are no surface streams or lakes on-site; industrial or commercial use would not be conducive to creation of either, thereby eliminating any reasonable anticipation of surface water use on-site to become a potential exposure pathway.

5.5.2.2. Groundwater.[7]

The groundwater beneath the site is not a current source of drinking water, nor will it be a source of drinking water in the future for the following reasons.[8, 9]

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[6] C-T Phase II Plan §3.6 Surface Water Hydrology.
[7] C-T Phase II DP §3.7 Groundwater Hydrology.
[8] Mallinckrodt. *RCRA Facility Investigation Report for AOC I (Site-Wide Groundwater)*, Mallinckrodt, Inc., St. Louis Facility, p. 5. April 6, 2001; prepared by URS Corporation.
[9] Ref. Appendix A herein.

1. All of the drinking water for the City of St. Louis is derived from the Mississippi and/or Missouri Rivers, and all of the drinking water intakes for the City of St. Louis are located upstream of the facility.

2. St. Louis City Ordinance 13,272, Section 3 (dated March 25, 1885), states that drinking water supply wells are prohibited within the City of St. Louis. The ordinance has restricted drinking water supply well installation in the City of St. Louis for over 100 years and will continue to restrict well installation for the foreseeable future.

3. There is no known drinking water well in the vicinity of the plant (DOE, 1990). According to information obtained from the Missouri Department of Natural Resources Division of Geology and Land Survey, two wells are located within a ½-mile radius of the facility (EPA, 1993). Neither of the wells is a drinking water well. Well No. 2798 is located in the SE¼ of Township 45N Range 7E. It was installed in 1933 to a depth of 185 feet and produced 30 gallons per minute. Fisher Chemical Company is listed as the well owner. Well No. 19835 is located in the SE¼ NE½ Township 45 N Range 7E and was installed in 1961. It is 180 feet deep and screened in the Mississippian alluvium. Well No. 19835 has produced 260 gallons per minute, but is located at an abandoned site.

4. The quality of perched groundwater in fill historically placed along the riverfront in the St. Louis area is naturally poor due to the presence of brick, glass, concrete rubble, coal cinder, and slag, and associated metals and PAH compounds (DOE, 1990). The perched zone is intermittent in nature and limited in its lateral continuity, saturated thickness, and transmissivity, which results in low water producing quality. For these reasons, the perched zone is not a realistic source of potable groundwater even in the absence of any contamination derived from the Mallinckrodt facility.

5. Groundwater in the lower zone (sandy alluvial unit) is locally saline and generally very hard, with high iron and manganese content. Groundwater found in the underlying bedrock is generally saline and non-potable. Groundwater in the site area is not withdrawn for potable, industrial, or agricultural purposes, and groundwater use is not anticipated to change in the future. Considering these unfavorable groundwater characteristics and that St. Louis has a municipal water system that serves this region, installation of a domestic water well is not reasonably foreseeable. Since the land is unsuitable for agriculture because it is coal cinder fill, withdrawal of groundwater for agricultural irrigation also is not a reasonable expectation.

6. Groundwater in the St. Louis area is generally of poor quality and does not meet drinking water standards without treatment. The expected future use of groundwater at the SLDS is minimal since in the Mississippi and Missouri Rivers constitute high-quality, large-quantity, readily available sources.[10]

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[10] USACE. Record of Decision for St. Louis Downtown Site. p. 6, July 1998.

5.6. CONCEPTUAL AND MATHEMATICAL MODELS

Each environmental scenario and pathway of exposure can be described by a conceptual model and a mathematical model. A *conceptual model* is a simplified description of the environmental system, including the radioactive source, its movement in the environment to a receptor, and habits of the receptor of the exposure. A *mathematical model* reduces the conceptual model into equations that can quantify the relations between radioactive source and radiological dose.

5.6.1. Soil

The RESRAD computer program implements mathematical models that calculate total effective dose equivalent to an average member of the critical group from residual radionuclides in soil. RESRAD models simulate environmental pathways including transport in air, water, and biological media to an exposed person. Exposure is translated to radiological dose with ICRP models (ICRP 26, 30, and 48) for estimating total effective dose equivalent, which are the bases of NRC regulations. Mathematical models implemented in RESRAD v.6 have been described [11] RESRAD v.6 includes perhaps the best available set of mathematical models to describe the environmental scenario and exposure pathways that might be anticipated in Plant 5 after C-T decommissioning.

5.6.2. Pavement

Land in Plant 5 that is not covered by a building is practically all paved with concrete or macadam. Characterization surveys have identified some radioactivity on pavement that is elevated above expected background. A conceptual model of this surficial source is described as 0.1 cm thick layer of contaminated soil at land surface. An industrial worker might be exposed to surficial contamination on pavement by:

- direct irradiation by the surficial source while out-of-doors;
- inhalation of suspended dust while out-of-doors;
- ingestion of dust;
- direct irradiation while indoors; and
- inhalation of suspended dust while indoors.

These potential exposure pathways are simulated by mathematical models in RESRAD v.6. An advantage of using RESRAD for exposure to contamination on pavement is consistency with the simulation of the conceptual model for exposure to bare soil. This is significant because the airborne dust loading model is used to estimate airborne concentration of respirable particulate for both the outdoor sources, soil and pavement.

[11] Yu, C., *et. al., User's Manual for RESRAD* Version 6. ANL/EAD-4. July 2001.

5.7. INPUT PARAMETERS

Default values of parameters in RESRAD v. 6 have been developed and described.[12] Unless described herein, default values of parameters in RESRAD v.6 have been retained in the derivation of DCGL. The influence of parameters most pertinent to the scenario have been considered for appropriateness of value.

5.7.1. Industrial Worker Worker Exposed to Soil

5.7.1.1. Area of Contaminated Zone

For the purpose of deriving, DCGL in soil, the area of a contaminated zone should not be smaller than 2,000 m^2 the maximum area of a Class 1 survey unit; nor should it be larger than 10,000 m^2, the maximum area of a Class 2 survey unit. The RESRAD v.6 default value is 10,000 m^2. The larger assumed potential area increases dose by airborne dust inhalation and thereby diminishes the DCGL. Thus, the default value, 10,000 m^2 is retained.

5.7.1.2. Thickness of Contaminated Zone

The thickness of the contaminated zone is the depth distance between the uppermost and lowermost soil samples that have radionuclide concentration above background.

Probabilistic. An analysis of the effect of contaminated zone thickness on radiological dose during industrial land use was done to interpret the depth beyond which additional contribution from a representative source in soil to irradiation dose to a person would become negligible. Essential features of modeling to perform this analysis were:

- a reasonably representative source ratio of 3 U series, 0.0455 x 3 actinide (U^{235}) series, and 1 Th series together.
- bare land in which residual source contamination extends from land surface downward into the soil;
- indoor time fraction = 0.0 in order to simulate effect of irradiation on bare land;
- the same industrial land use scenario modeled to derive $DCGL_W$ originally, except absent ingestion of soil and inhalation of dust; (for the origin of inadvertently ingested dust and of dust suspended into air is surficial topsoil); and
- deterministic simulation using RESRAD to derive the effect of increasing contamination depth in soil on exposure to direct irradiation.

The result of this analysis is summarized graphically in Figure 5-1. It determined that, in representative simulation, maximum dose rate by direct irradiation is reached asymptotically when the depth of the contaminated zone in topsoil reaches about 30 cm. Additional source thickness would not produce significantly greater dose rate.

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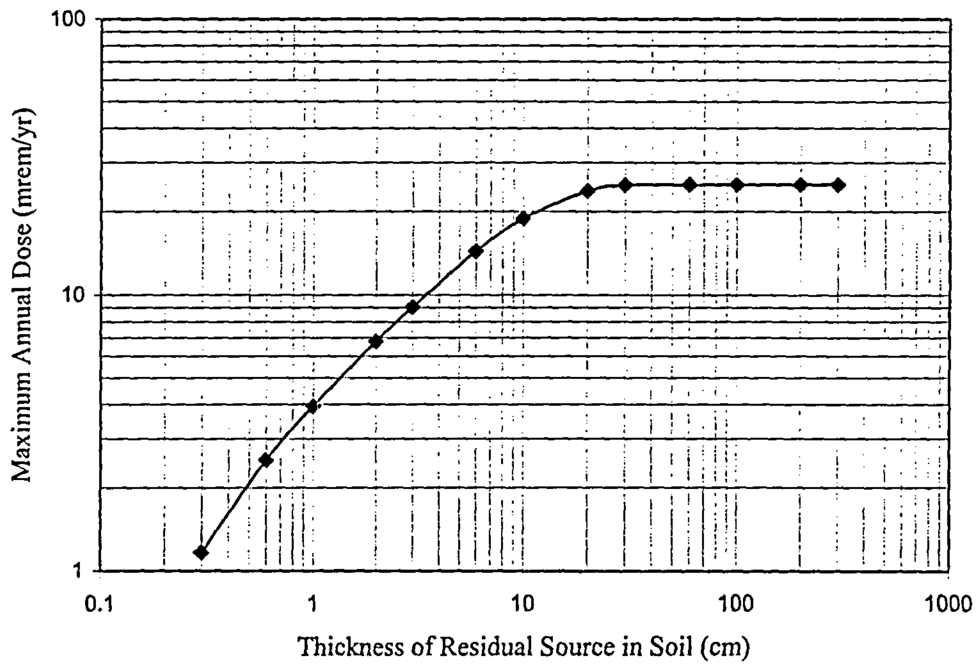
[12] Biwer, B.M., *et. al.*, "Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes." atch. C in *Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes.* NUREG/CR-6697. Dec. 2000.

Figure 5-1. Maximum Annual Radiological Dose Versus Source Depth in Soil
(infinitely-thick source ratio 3 U series + 1 Th series produces 25 mrem/yr)



As a result of this analysis, the thickness of contaminated zone parameter will be represented as a variable in probabilistic dose modeling. It is being represented as a uniform distribution ranging from 0 to 1 meter thick since characterization survey soil sampling intervals are insufficient to resolve a well-defined gradient within this range. A maximum depth of 1 meter is more than sufficient to be a conservative representation insofar as direct irradiation is concerned.

5.7.1.3. Cover Depth

Cover depth is the distance from ground surface to the contaminated zone. The default value in RESRAD is zero meters. Although Plant 5 is covered by pavement, when evaluating potential exposure to contaminated soil, it will be modeled as if there were no pavement and the land were bare.

5.7.1.4. Soil Mixing Layer Thickness

The soil mixing layer thickness is the thickness of the uppermost soil layer in which radioactive residue is mixed. It is estimated[13] to range from 0 to 0.6 meter, with the most likely thickness being 0.15 m. Since 0.15 m is also the default value, it will be assumed in DCGL calculations.

5.7.1.5. Occupancy Time

Occupancy times are described as the fraction of a year spent indoors and the fraction of a year spent outdoors in an area on-site that was previously contaminated. That would be the fraction

[13] *op. cit.*, Biwer, B.M., *et. al.*, pp. 3-42 & 3-43.

of an 8766 hour year spent in an industrial scenario within an affected area of Plant 5 or where the C-T incinerator or URO burials had been located.

An *industrial or commercial work* year is estimated to be 50 weeks x 40 hr/wk = 2000 hr. 0.8 of that time is estimated to be indoors and 0.2 is estimated to be out-of-doors. These amount to 0.1825 of time indoors and 0.04566 of time out-of-doors. These fractions, 0.1825 of time indoors and 0.04566 of time out-of-doors, are based on an estimated 2000 working hours per year and are entered into RESRAD as deterministic estimates of indoor and outdoor time fractions of 8766 hr/yr.

By comparison, the USACE estimated industrial worker occupancy 0.1969 of time indoors and 0.04566 out-of-doors on nearby Plant 2;[14] while the ANL staff estimated industrial worker occupancy indoors to be 0.17 of the time and occupancy out-of-doors to be 0.06 of the time.[15]

5.7.1.6. Inhalation Rate

It is necessary to estimate the volume of air inhaled by a worker while in an area on-site that was previously contaminated in order to estimate potential radiological dose to an industrial worker after C-T decommissioning. That volume is the product of occupancy time and inhalation rate. Resource data on inhalation rate have been reviewed.[17]

For the purpose of deriving DCGL in soil, industrial workers are assumed to spend time out-of-doors on affected land as well as indoors. The RESRAD model accepts a single inhalation rate, which should be weighted to represent both circumstances. The USACE[18] estimates an industrial worker breathes at an average rate of 1.2 m^3/hr. The ANL staff estimates that an industrial worker breathes at an average rate of 1.3 m^3/hr.[19] Short-term inhalation rates of adults[20] at 1.0 m^3/hr during light activity 1/3 of the time and at 1.6 m^3/hr during moderate activity 2/3 of the time produce a time and activity weighted inhalation rate of 1.4 m^3/hr. Similarly, if an outdoor worker[21] breathes 1.1 m^3/hr during slow activity 0.25 of the time and 1.5 m^3/hr during moderate activity 0.75 of the time, the weighted inhalation rate would also be estimated to be 1.4 m^3/hr. An inhalation rate of 1.4 m^3/hr has also been recommended as the default rate for commercial or industrial building occupancy.[22] An inhalation rate representing an *industrial* worker who spends some time out-of-doors and the majority indoors is represented by 1.4 m^3/hr in the industrial work scenario.

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14 USACE. Post-Remedial Action Report for the St. Louis Downtown Site Plant 2 Property. Table B-3. June 2001.

15 Yu, C., *et. al.*, ANL/EAD-4, Table 2-3, p. 2-22.

16 *ibid.*, USACE.

17 Biwer, B.M., *et. al.*, atch C, pp. 5-1 thru 5-5 in NUREG/CR-6697.

18 USACE. Post-Remedial Action Report for the St. Louis Downtown Site Plant 2 Property. Table B-3. June 2001.

19 Yu, C., *et. al.*, *User's Manual for RESRAD Version 6. ANL/EAC-4. p.2-22. July 2001.*

20 Biwer, B.M., *et. al.*, p. 5-4, Table 5.1-2.

21 Biwer, B.M., *et. al.*, p. 5-4, Table 5.1-2.

22 Biwer, B.M., *et. al.*, atch C, p. 5-3 in NUREG/CR-6697

Construction worker activity would seem to be most nearly similar to gardening, for which the recommended[23] default inhalation rate is 1.7 m^3/hr. This would correspond to an outdoor worker[24] whose activity is 0.8 moderate exertion at 1.5 m^3/hr breathing rate and 0.2 heavy exertion at 2.5 m^3/hr breathing rate. Since *construction* workers are assumed to work out-of-doors entirely, the inhalation rate of this critical group is estimated to be 1.7 m^3/hr without adjustment for any time indoors.

By comparison, the USACE estimates a breathing rate of 1.2 m^3/hr represents both industrial workers and construction workers on portions of Mallinckrodt's site being remediated under the FUSRAP.

5.7.1.7. Mass Loading for Inhalation

Estimation of intake by inhalation depends on the airborne concentration of contaminated airborne particulate matter, *i.e.*, soil, that is respirable. Respirable particles are those less than 10 μm in diameter. About 0.28 to 0.33 of airborne particles have been found to be respirable.[25, 26, 27, 28] The mass loading of respirable particulate in air may be estimated as the product of the total mass loading of airborne dust and the respirable fraction.

Deterministic. The total mass loading of airborne dust in an urban area has been estimated to range from 60 to 220 μg/m^3 by USHEW[29] and 33 to 254 by Gilbert, *et.al.*[30] A best geometric estimate is about 115 μg/m^3. Thus, a reasonable estimate of respirable mass loading for inhalation in an urban, industrial area is 0.3 x 115 μg/m^3 = 35 μg/m^3. (This is about the upper 90th percentile recommended for use in RESRAD in a residential environment.[31] Long-term measurements of mass loading in ambient air are 23 μg/m^3 at the 50th percentile.)

Probabilistic. The model of radionuclides in outdoor air subject to inhalation is the product of the radionuclide concentration in surface soil and the airborne density of particulates of respirable size in ambient air. Biwer, *et.al.*,[33] summarized the distribution of respirable

23 Biwer, B.M., *et. al.*, p. 5-4, Table 5.1-3.
24 Biwer, B.M., *et. al.*, p. 5-4, Table 5.1-2.
25 USEPA. *Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment.* EPA 520/4-77-016. pp. 31-32. Sept. 1977.
26 Chepil, W.S., "Sedimentary Characteristics of Dust Storms: III Composition of Suspended Dust." Am. J. Sci., 225, p. 206, 1957. in EPA 520/4-77-016, p. 57
27 Sehmel, G.A., *Radioactive Particle Resuspension Research Experiments on the Hanford Reservation*, BNWL-2081, 1977.
28 Willeke, K. *et.al.*, "Size Distribution of Denver Aerosols - A Comparison of Two Sites," Atm. Env., 8, p. 609, 1974.
29 USHEW. *Air Quality Criteria for Particulate Matter.* 1969. in NUREG/CR-5512, 1, p. 6.11.
30 Gilbert, T.L., *et.al.*, *Pathways Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites.* ORO-832 rev. Jan 1984. in Yu, C. *et.al.*, *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. pp. 110-111, Apr. 1983.
31 Biwer, *et.al.* atch C, p. c4-16 in NUREG/CR-6697.
32 NUREG/CR-5512, 1, p. 6.11.
33 Biwer, *et.al.* "Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes." atch C, pp. C4-15 & C4-16 in NUREG/CR-6697. Dec. 2000.

particulate in ambient air reported by the EPA[34] for about 1790 air monitoring stations in a range of environments. At cumulative probability = 0.50, the most frequent respirable particulate density in the EPA distribution occurs at about 23 μg/m³ air.[35]

Three other sources of data were examined to get more comprehensive information about airborne particulate density in urban air. The total mass loading of airborne dust in an urban area has been estimated to range from 60 to 220 μg/m³ by USHEW[36] and 33 to 254 by Gilbert, *et.al.*[37] Their respective geometric means are approximately 115 and 92 μg/m³. Airborne particulates measured in 14494 urban and 3114 non-urban air samples in the National Air Sampling Network exhibited a geometric mean of 98 μg/m³.[38] A best geometric estimate of those is about 102 μg/m³.

Estimation of intake by inhalation depends on the airborne concentration of contaminated airborne particulate matter, *i.e.*, soil, that is respirable. About 0.28 to 0.33 of airborne particles have been found to be respirable, *i.e.*, less than 10 μm in diameter.[39, 40, 41, 42] The mass loading of respirable particulate in air may be estimated as the product of the total mass loading of airborne dust and the respirable fraction. Thus, a reasonable estimate of the geometric mean of respirable mass loading for inhalation in an urban, industrial area is about 0.3×102 μg/m³ = 31 μg/m³.

A distribution representing airborne particulate loading in urban air may be estimated by the shape of the distribution in NUREG/CR-6697, Table 4.6-1 and shifted upward by an increment representing the increase in dust in urban air relative to all ambient air. The result, in Figure 5-2, becomes the probabilistic distribution to replace the default distribution in RESRAD v. 6.3. This distribution represents careful, reasonable appraisal of values of airborne mass loading in an urban environment.

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34 USEPA. Aerometric Information Retrieval System. internet site http://www.epa.gov/airs/airs.html. 1999.

35 Biwer, *et.al.*, Table 4.6-1 and Fig. 4.6-1 in NUREG/CR-6697.

36 USHEW. *Air Quality Criteria for Particulate Matter.* 1969. in NUREG/CR-5512, 1, p. 6.11.

37 Gilbert, T.L., *et.al.*, *Pathways Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites.* ORO-832 rev. Jan 1984. in Yu, C. *et.al.*, *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. pp. 110-111, Apr. 1983.

38 Stern, A.C., ed. *Air Pollution.* 2nd ed. Academic Press. NY. 1968.

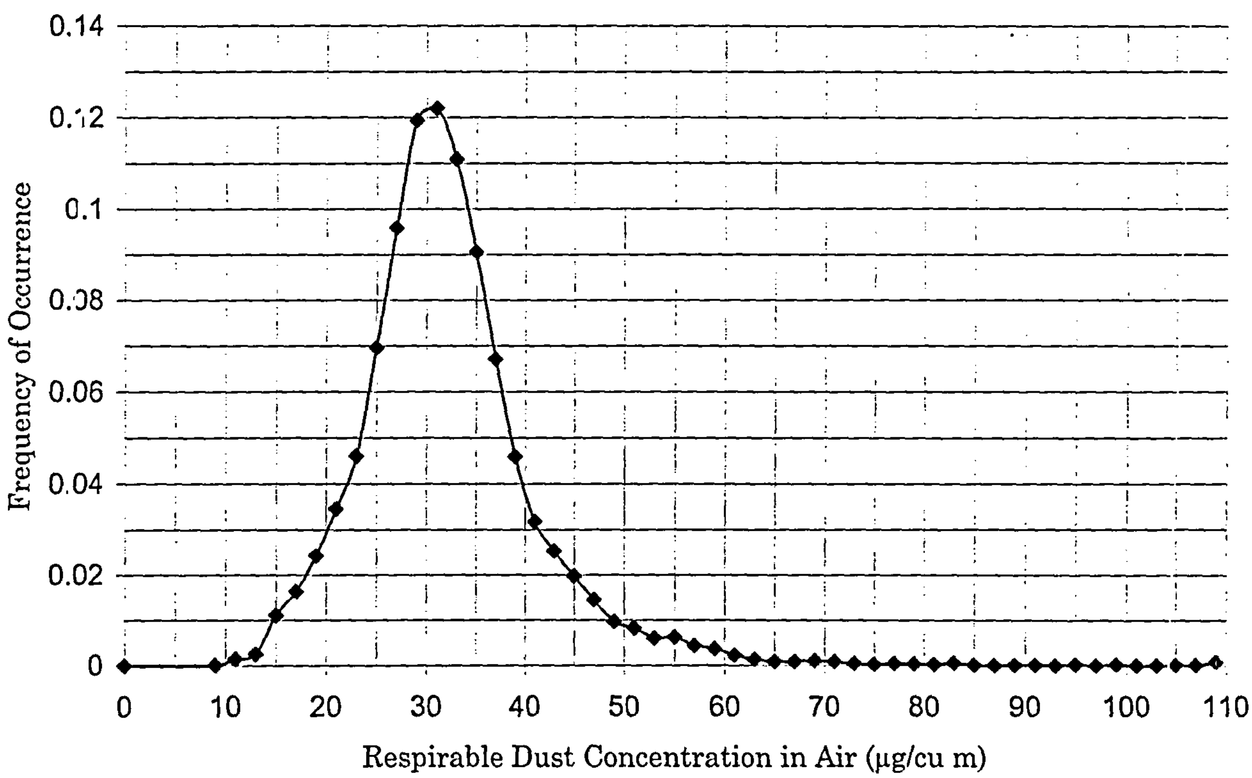
39 USEPA. *Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment.* EPA 520/4-77-016. pp. 31-32. Sept. 1977.

40 Chepil, W.S., "Sedimentary Characteristics of Dust Storms: III Composition of Suspended Dust." Am. J. Sci., 225, p. 206, 1957. in EPA 520/4-77-016, p. 57

41 Sehmel, G.A., *Radioactive Particle Resuspension Research Experiments on the Hanford Reservation,* BNWL-2081, 1977.

42 Willeke, K. *et.al.*, "Size Distribution of Denver Aerosols - A Comparison of Two Sites," Atm. Env., 8, p. 609, 1974.

Figure 5-2. Frequency Distribution of Respirable Dust in Urban Air
(EPA AIRS PM-10 data normalized to urban environment)



It is represented in RESRAD as a continuous linear distribution with entries in Table 5-1.

Table 5-1. Respirable Particulate in Urban Air

Respirable Particulate Concentration (µg/m^3)	Frequency
0.	0.0
15.	0.0151
23.	0.1365
37.	0.8119
47.	0.9495
67.	0.9937
83.	0.9983
107.	0.9992

5.7.1.8. Soil Ingestion Rate

The quantity of contaminated soil ingested incidentally from outdoor activities annually is estimated to range from 0 to 36.5 g/yr.[43] The most likely amount is estimated to be 18.3 g/yr.[44] The recommended default value[45], 36.5 g/yr, is entered into RESRAD to represent an industrial worker.

5.7.1.9. Building Shielding Against Gamma Irradiation

The floor and walls of a building shield an occupant against some gamma rays entering from soil outside. Buildings in Plant 5 have concrete slab floors and brick or concrete block walls with few windows.

Probabilistic. An analysis of the effect of radiation attenuation by a building, especially floor thickness, on radiological dose for the portion of time a worker spends indoors during industrial occupation has been performed. Essential features of modeling to perform this analysis were:

- a reasonably representative source ratio of 3 U series, 0.0455 x 3 actinide (U^{235}) series, and 1 Th series together;
- residual source contamination extends from land surface downward one meter into the soil;
- outdoor time fraction = 0.0 in order to simulate effect of irradiation indoors;
- the same industrial land use scenario modeled to derive $DCGL_W$ originally, except absent ingestion of soil and inhalation of dust;
- deterministic simulation using RESRAD to derive the fraction of gamma dose rate as a function of concrete floor thickness; and
- combination of probable distribution of floor thickness and indoor gamma shielding factor to derive a probability distribution of indoor gamma shielding factor.
- The result of this analysis is summarized in Table 5-2 where indoor gamma shielding factor probability distribution is tabulated.

On the premise that a floor construction is likely to be specified in an integer thickness in units of inches, a *discrete cumulative* probability distribution of these data has been specified in RESRAD. Table 5-2 depicts the cumulative probability and indoor gamma shielding factor data entered into RESRAD for probabilistic evaluation of the effect of this parameter on radiological dose rate.

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43 Biwer, *et.al.* atch C, pp. c5-19 thru c5-25 in NUREG/CR-6697.
44 *ibid.*
45 Yu, C., *et. al.*, NUREG/CR-6697, p. 18, Table 2.1.
46 Biwer, *et.al.* atch C, p. c7-36 in NUREG/CR-6697

Table 5-2. Indoor Gamma Shielding Factor Distribution				
Shielding Thickness		Shielding Factor	Fractional Occurrence	Cumulative Distribution Indoor Only
(cm)	(in)	("value")		(cdf)
25.4	10	0.0084	0.01	0.01
20.3	8	0.022	0.08	0.09
17.8	7	0.035	0.12	0.21
15.2	6	0.055	0.18	0.39
12.7	5	0.088	0.24	0.63
10.2	4	0.14	0.25	0.88
7.6	3	0.23	0.07	0.95
0	0	1.0	0.05	1.0

5.7.1.10. Indoor Airborne Dust Filtration

The fraction of airborne dust out-of-doors that is available indoors has been reviewed.[47] When considering outdoor sources of respirable particulate indoors, Wallace[48] estimated the indoor-to-outdoor fraction to be close to 0.5. In residential housing, Wallace estimated the indoor-to-outdoor fraction of respirable particulate to average about 0.57. Biwer, *et. al.*,[49] estimated the same fraction to be 0.54. A value of 0.6 will be assumed when deriving DCGL for an industrial worker scenario.

5.7.1.11. Wind Speed

The average wind speed reported for St. Louis is 4.3 m/s (9.5 mi/hr);[50] whereas the default value in RESRAD v. 6 is 2 m/s. Although it makes little difference in dose modeling, an average wind speed = 4. m/s is entered into RESRAD to derive DCGL for C-T decommissioning.

5.7.2. Industrial Work on Pavement

The influences of parameters most pertinent to industrial work on pavement scenario are discussed below. Industrial worker characteristics are assumed to be the same whether the source is in soil or on pavement. Aside from parameters mentioned below, default values of parameters in RESRAD v.6 have been retained when deriving DCGL for surficial contamination on pavement.

5.7.2.1. Contaminated Zone

Surficial contamination on pavement may be simulated in RESRAD as a thin contaminated layer

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47 Biwer, *et.al.* atch C, pp. 7-1 thru 7-4 in NUREG/CR-6697

48 Wallace, L., "Indoor Particles: A Review." J. Air & Waste Mgt. Assoc., 46, pp. 98-126. 1996 in Biwer, *et.al.* atch C, pp. 7-1 thru 7-4 in NUREG/CR-6697.

49 Biwer, *et.al.* atch C, pp. 7-3 & 7-4 in NUREG/CR-6697.

50 C-T Phase II Decommissioning Plan, §3.4, Table 3-2.

of soil without cover and with zero erosion rate. Inhalation and ingestion models in RESRAD depend more on radionuclide concentration in soil than on thickness; while direct irradiation is more closely related to thickness, particularly when the source is thin. Physically, one would not expect as much as 0.1 cm of soil, on average, on pavement in Plant 5.

Consequently, an areal density of soil equivalent to 0.3 cm thickness of soil would adequately represent areal contamination on pavement for the purpose of estimating potential exposure of an industrial worker. Areal contamination on pavement is thus represented by 0.3 cm thick contaminated zone, zero cover depth, and zero erosion rate.

Although characterization survey data suggest surface contamination is unlikely to exceed an appropriate areal DCGL, assumption of 10,000 m^2 area of contamination will tend to maximize the dose factor and minimize the DCGL. Hence, the default value of the contaminated area, 10,000 m^2, is retained for pavement.

5.7.2.2. Wind Speed and Mass Loading for Inhalation

The average wind speed reported for St. Louis is 4.3 m/s (9.5 mi/hr);[51] whereas the default value in RESRAD v. 6 is 2 m/s. Thus, an average wind speed = 4. m/s is entered into RESRAD to derive an areal DCGL for decommissioning pavement affected by C-T.

A mass loading of respirable dust in outdoor air = 35 $\mu g/m^3$ has been entered into RESRAD to simulate an industrial work scenario in which the radioactive source is surficial contamination on pavement. The rationale of a dust concentration, 35 $\mu g/m^3$, in outdoor air is discussed in section 5.7.1.7.

While a worker is indoors, an indoor dust filtration factor = 0.6 will be assumed when deriving DCGL. The rationale for estimating this value is discussed in section 5.7.1.10.

5.7.2.3. Worker Characteristics

Industrial workers spend most of their time indoors. In Plant 5, an industrial worker is conservatively assumed to be on contaminated pavement 0.20 of their work time, which is an outdoor time fraction = 0.04563, and their remaining time indoors, an indoor time fraction = 0.1825. These estimates are discussed in section 5.7.1.5.

Where the source of contamination is on the surface of pavement, an industrial worker is assumed to ingest contaminated material at RESRAD's default rate, 36.5 grams per year.

A breathing rate representative of indoor and outdoor activities is estimated to be 1.4 m^3/hr, or 12270 m^3 during a 2000 work year. While indoors, an external gamma shielding factor = 0.17 of the outdoor gamma exposure rate is estimated to apply in Plant 5 buildings, which typically are constructed with a concrete slab floor and brick walls. These estimates are discussed in sections 5.7.1.6, 5.7.1.9, and 5.7.1.10.

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[51] C-T Phase II Decommissioning Plan, §3.4, Table 3-2.

5.8. DCGL FOR INDUSTRIAL WORK ON SOIL

5.8.1. Radiological Dose Modeling

Models simulating environmental exposure pathways to estimate potential radiological dose to people are coded in the RESRAD computer program. With the aid of RESRAD, probabilistic modeling has been done to derive dose factors and DCGL at the *peak of the mean* dose as NRC guidance suggests.[52]

RESRAD is able to compute and tabulate the time of peak mean dose rate and the peak mean dose rate (mrem/yr). One may derive a composite dose factor for a related series of radionuclides by summing the average dose of each source radionuclide in the series at the time of the peak of the mean dose. Then one may derive the dose factor as the quotient of that sum and the concentration of the radionuclides to which it is referenced. For example, the composite dose factor of the thorium series would be the sum of doses of the principal radionuclides, including their short-lived progeny, at the time of the peak of the mean dose divided by the initial concentration of the reference, or parent Th^{232}.

In the probabilistic total dose summary, one can read the contribution by each long-lived radionuclide entered in the source term column corresponding to the time of peak mean dose. The *average (avg)* dose of each source radionuclide at the time of peak mean dose, summed over all of the source radionuclides, equals the peak of the mean dose. Having identified the contribution of each source radionuclide to the peak of the mean total dose, one may derive an appropriate probabilistic dose factor (mrem/yr per pCi/g) as the quotient of the average dose of each source radionuclide at the time of peak mean total dose and the concentration of that radionuclide entered into the source term in RESRAD.

5.8.2. Derivation of Thorium Series Dose Factor and $DCGL_W$

Thorium series nuclides associated with C-T processing have grown or decayed within about 0.20 of radioactive equilibrium. Considering that C-T feed was ore and that alpha spectrometry of separate radioelements poses some uncertainty at low concentration, the thorium series might rationally be assumed to be in radioactive equilibrium in Plant 5 soil samples. Especially for future estimation, the shorter radioactive half-lives of Ra^{228}, 6.7 yr, and of Th^{228}, 1.9 yr, imply that Th^{232} parent concentration is controlling. Characterization survey data also indicate the thorium series occurs at about a 1/3 of the uranium series concentration in soil.

Assuming the thorium series to be in radioactive equilibrium, a composite dose factor representing the series was derived probabilistically with RESRAD (ref. case 408guti in Appendix C). Equal concentrations of principal radionuclides, Th^{232}, Ra^{228}, and Th^{228}, entered into RESRAD, produce peak of the mean annual dose at year zero and corresponding peak of the mean composite dose factor, DF = 1.05 (mrem/yr)/(pCi Th^{232}/g soil). The corresponding $DCGL_W$ = 23.8 pCi Th^{232}/g soil for industrial land use.

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[52] NUREG-1757, 2, §5.

[53] Composite limit is also referred to as the derived concentration guideline level for the Wilcoxon test ($DCGL_W$).

5.8.3. Derivation of Uranium Dose Factor and $DCGL_W$

Since C-T residue includes natural uranium, it would be logical to consider U^{238} through U^{234} and include the actinium, or U^{235}, series in its naturally-occurring proportion to the uranium series. When these radionuclides are the source in a RESRAD probabilistic simulation of an industrial land use scenario, the peak of the mean annual dose occurs in the first year of exposure (ref. case 407guti in Appendix C). The composite dose factor,[54] corresponding to the peak of the mean annual dose rate = 0.0347 mrem/yr per pCi U^{238}/g soil. The corresponding $DCGL_W$ = 721 pCi U^{238}/g soil for industrial land use.

5.8.4. Derivation of the Dose Factor and $DCGL_W$ of Th^{230} and Ra^{226}

Since Th^{230} transmutes into Ra^{226}, is observed together with Ra^{226} in soil samples, and since the dose factor of Ra^{226} and its progeny, including Pb^{210}, exceed other radionuclides in the uranium series, it is logical to associate Th^{230} and Ra^{226} in dose estimation. Measurement of Th^{230} requires analysis that is slow, expensive, and separate from other key radionuclides. To the extent its presence in excess of uranium or Ra^{226} does not increase potential annual dose substantially and specific measurement is unnecessary, remediation can be done without undue delay. It would be desirable to adopt a conventional association that does not underestimate potential radiological dose and that allows measured Ra^{226} to represent the subseries. For this reason, it would be logical and useful to link Th^{230} with Ra^{226} in lieu of further measurement of Th^{230} itself.

A subseries beginning with Th^{230} and including Ra^{226}, Pb^{210}, and their short-lived progeny is a logical grouping. In soil, it would be reasonable to assume Ra^{226}, Pb^{210}, and their short-lived progeny are in radioactive equilibrium; although exhalation of Rn^{222} could even leave progeny below equilibrium. The relatively short half-life of Pb^{210}, 21 years, and its lower dose factor than of Ra^{226} justifies compositing the contributions of Ra^{226}, Pb^{210}, and their short-lived progeny to radiological dose.

A series of probabilistic dose modeling was computed with RESRAD to determine conditions in which a composite dose factor including principal radionuclides, Th^{230}, Ra^{226}, and Pb^{210} as the source, would not significantly underestimate radiological dose when applied to the range of characterization survey data. Within a population of more than 500 soil characterization samples and among the 41 pairs in which Ra^{226} and Th^{230} are above background mean by more than 1 standard deviation, only 3 samples, or 0.6 %, exhibit Th^{230} -to- $U^{238} > 6$. Adopting the composite dose factor representing Th^{230}, Ra^{226}, Pb^{210}, and their progeny, with Th^{230}/Ra^{226} ratio = 6, would be expected to encompass more than 99% of soil samples. The peak of the mean dose as a function of increasing Th^{230} -to- the peak of the mean dose when Th^{230} concentration equals Ra^{226} concentration only exceeds 1.1, or increases by as much as 11 percent only when the Th^{230} -to- U^{238} ratio exceeds 6. Thus, radiological dose is not very sensitive to increasing Th^{230} -to- Ra^{226} ratio.

Thus, it is reasonable to apply a composite dose factor = 0.852 (mrem/yr)/(pCi Ra^{226}/g soil) and a $DCGL_W$ = 29.4 pCi Ra^{226}/g soil to represent the subseries including Th^{230}, Ra^{226}, and Pb^{210} for

[54] including all the principal radionuclides and their short-lived progeny

industrial land use.

5.8.5. Composite Dose Factors and $DCGL_W$

From the separate cases and source terms, recorded in Appendix D, composite dose factors and $DCGL_W$ in Table 5-3 were derived.

Table 5-3. Composite Dose Factor and DCGLw Derived Separately

Radionuclide Group	Composite Dose Factor[55] (mrem/yr)/(pCi/g)	$DCGL_W$ [20] (pCi/g)	RESRAD case
Th series	1.05	23.9	408guti
Natural Uranium	0.0347	721.	407guti
6 Th^{230} + Ra^{226} + Pb^{210}	0.852	29.4	399guti

Dose factor and $DCGL_W$ of the thorium series is referenced to Th^{232}.
Dose factor and $DCGL_W$ of natural uranium is referenced to U^{238}.
Dose factor and $DCGL_W$ of Th^{230}, Ra^{226}, and Pb^{210} is referenced to Ra^{226}.

5.8.6. Compliance Model for Soil

In the uranium series, U^{238} through U^{234} will be assumed to be in radioactive equilibrium and will be represented by measurement of uranium isotope(s) or surrogate progeny. The actinium (U^{235}) series will be assumed to exist in its naturally-occurring proportion to the uranium series.

Radium-226 and its progeny, including Pb^{210}, will be assumed to be in radioactive equilibrium and will be referenced to measured Ra^{226} concentration. Th^{230} will be associated with Ra^{226} and Pb^{210} because the Ra^{226}, to which it decays, presents the dominant dose factor.

Thorium series radionuclides will be assumed to be in radioactive equilibrium and will be represented by measurement of a surrogate radionuclide, Ac^{228}, in the series.

Radiological **dose factors** of individual radionuclides in each subseries may then be composited and stated simply as

$$DF_U = [D(U^{238}) + D(U^{234}) + D(U^{235} + Ac^{227} + Pa^{231})] \div C(U^{238}) \quad \text{eqn 1}$$

$$DF_{Ra226\ \&\ Th230} = [D(Ra^{226}) + D(Pb^{210}) + D(Th^{230}{=}6\ Ra^{226})] \div C(Ra^{226}) \quad \text{eqn 2}$$

$$DF_{Th\ series} = [D(Th^{232}) + D(Ra^{228}) + D(Th^{228})] \div C(Th^{232}) \quad \text{eqn 3}$$

where D_i = annual dose rate of principal radionuclide *i* and its short-lived progeny at the time of the peak of the mean dose rate posed by the related group of radionuclides (mrem/yr)

C_i = concentration of reference radionuclide *i* in soil (pCi/g soil)

DF = radiological dose factor (mrem/yr)/(pCi/g soil)

Dose factors include long-lived radionuclides mentioned and their short-lived progeny.

The **derived concentration guideline level** may then be stated as

[55] DF and $DCGL_W$ are referenced to Th^{232}, U^{238}, and Ra^{226} respectively.

$$DCGL_{W\,U} = \frac{25}{DF_U} \qquad \text{eqn 4}$$

$$DCGL_{W\,Ra226} = \frac{25}{DF_{Ra226+Th230}} \qquad \text{eqn 5}$$

$$DCGL_{W\,Th\,series} = \frac{25}{DF_{Th\,series}} \qquad \text{eqn 6}$$

where 25 = maximum acceptable annual radiological dose (mrem/yr)
$DCGL_W$ = derived concentration guideline level of reference radionuclide (pCi/g soil)

This permits a simplified statement of the **sum-of-fractions** of the radionuclides encountered in C-T decommissioning to be:

$$SOF = \frac{C_{U238}}{DCGL_{W\,U}} + \frac{C_{Ra226}}{DCGL_{W\,Ra226}} + \frac{C_{Th232}}{DCGL_{W\,Th\,series}} \qquad \text{eqn 7}$$

where:
SOF = sum-of-fractions of $DCGL_W$
C_{U238} = concentration of U^{238} in soil (pCi/g)
C_{Ra226} = concentration of Ra^{226} in soil (pCi/g)
C_{Th232} = concentration of Th^{232} in soil (pCi/g)
$DCGL_{W\,U}$ = $DCGL_W$ of $U^{238} + U^{234}$ + actinium (U^{235}) series in its naturally-occurring ratio to the uranium series (pCi/g)
$DCGL_{W\,Ra226}$ = $DCGL_W$ of 6 $Th^{230} + Ra^{226}$ and its progeny, including Pb^{210}, in radioactive equilibrium (pCi/g)
$DCGL_{W\,Th\,series}$ = $DCGL_W$ of Th^{232} and its progeny, including Ra^{228} and Th^{228}, in radioactive equilibrium (pCi/g)

The index, or SOF, determined for each soil sample or location measured, will be the basis of testing compliance with population statistics and elevated measurements criteria.

5.8.7. Area Factor for Elevated Measurements in Soil

It is desirable to discover any small area of contamination that could cause more than 25 mrem/yr radiological dose. The magnitude by which the concentration within a small area of elevated radioactivity can exceed the $DCGL_w$ while maintaining compliance with the release criterion is defined as an *area factor*.[56] It may be calculated as the ratio

$$\text{Area Factor} = \frac{\text{composite dose factor for survey unit area}}{\text{composite dose factor for local area of contamination}} \qquad \text{eqn 8}$$

Figure 5-3 is the *area factor* as a function of a localized area of radioactive contamination consisting separately of

- thorium series;
- natural uranium, including U^{234}, U^{235}, and actinium series in which uranium isotopes are in the ratio occurring in natural uranium; and
- Ra^{226}, Pb210, and 6 Th^{230}.

[56] MARSSIM, p. 5-36. Dec. 1997.

The maximum tolerable areal density of residual radioactive contamination by each of these groups, above background, within a small area of elevated radioactivity is derived by the relation

$$DCGL_{EMC} = \text{Area Factor} \times DCGL_w$$

where the maximum area factor considered corresponds to 10 m^2 area of elevated contamination.

An index representing radioactivity in a small area may be calculated with the sum-of-fractions relation:

$$\text{Index} = \frac{C_{U238}}{(AF \times DCGL_W)_U} + \frac{C_{Ra226}}{(AF \times DCGL_W)_{Ra226}} + \frac{C_{Th232}}{(AF \times DCGL_W)_{Th\,series}} \qquad \text{eqn 9}$$

where $DCGL_W$ are read from Table 5.1 and AF_U, AF_{Ra226}, and $AF_{Th\,series}$ are read from Figure 5-3. This Index represents the fraction or multiple of the $DCGL_{EMC}$. In effect, $DCGL_{EMC}$ occurs when this Index = 1 and is exceeded when the Index > 1.

Systematically distributed measurements and soil characterization survey measurements, together, are employed in each Class 1 survey unit to find such an area of contamination whose radioactivity concentration is elevated above the $DCGL_w$.

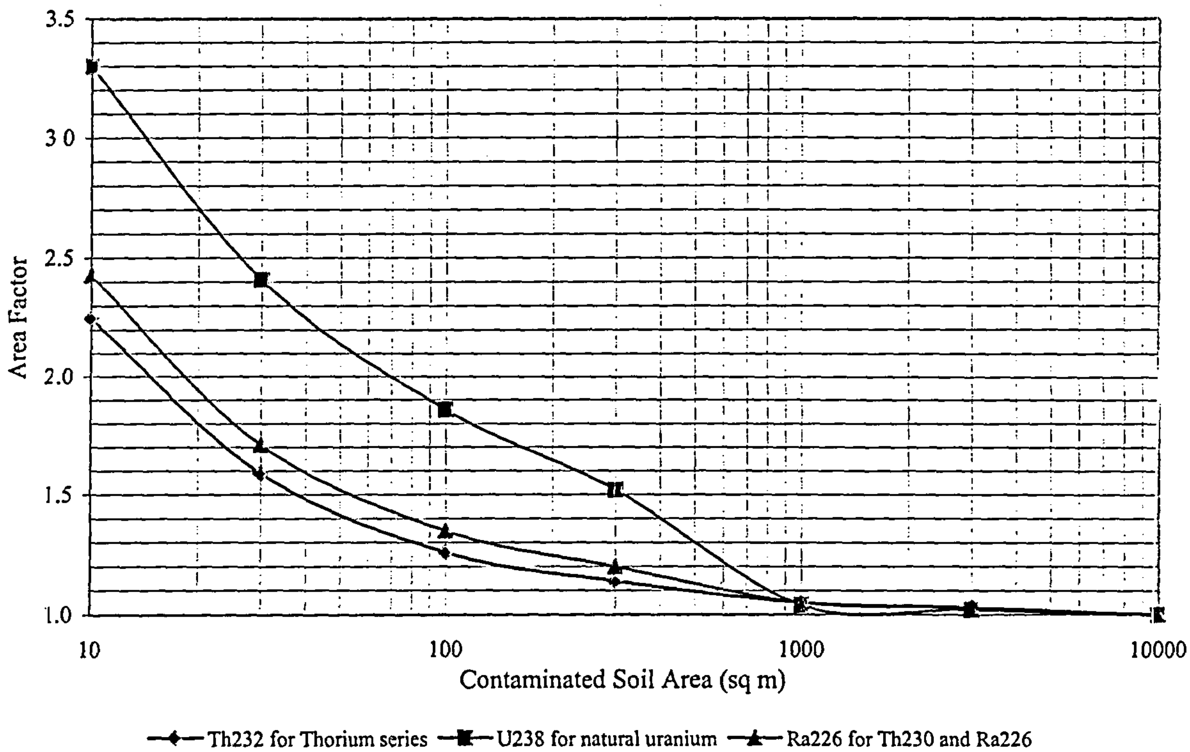

Figure 5-3. Area Factors for Elevated Measurements Criterion in Soil

5.9. INDUSTRIAL WORK ON PAVEMENT

5.9.1. $DCGL_W$ on Pavement

Dose factors were computed by RESRAD for an industrial work scenario on pavement.

Dose factors were computed by RESRAD for an industrial work scenario on pavement. The RESRAD output for each radionuclide can be interpreted as a dose factor (mrem/y per pCi/m^2), which in turn may be interpreted as a maximum acceptable average areal density of the radionuclide on a surface, also called the $DCGL_w$, corresponding to a maximum acceptable potential radiological dose equivalent.

Exposure to bare soil and to pavement cannot occur simultaneously. The scenario assuming bare soil necessarily excludes pavement and any exposure to it. Thus, derivation of DCGL for work on soil is independent of exposure to pavement.

On the other hand, pavement would exist atop soil. When so, it would be a complete barrier against airborne and ingestion pathways of exposure to conceivable residue in the soil and an incomplete shield against gamma radiation penetrating from conceivable residue in the soil. With the aid of dose modeling of outdoor exposure to gamma radiation penetrating nominal 4-inch-thick pavement by RESRAD, 2 meters of soil containing $DCGL_W$ concentration of 3 U-to-1 Th series source would be estimated to contribute 3.8 mrem/yr through the pavement. Subtracting that from 25 mrem/yr allotted to DCGL would imply reduction of conceivable contribution from residue on pavement itself to 21.2 mrem/yr, or 0.85 of the $DCGL_W$ derived and proposed for pavement.

Although it is unlikely that both soil and pavement would be contaminated to more than 0.85 of either $DCGL_W$, and thus are practically independent, $DCGL_W$ in Table 5-4 and consequently $DCGL_{EMC}$ are reduced to 0.85 of values that would produce 25 mrem/yr. Corresponding $DCGL_W$ were then derived as the quotient of 21.2 mrem/yr and each dose factor. The adjusted $DCGL_W$ applicable to pavement are in Table 5-4. Application of $DCGL_W$ in Table 5-4 absorbs any need to allocate potential radiological dose among soil and pavement later.

The input and output for the RESRAD runs used in this analysis are listed in Appendix D of this Plan.

Table 5-4. Uranium Series and Thorium Series Limits on Pavement Surface Producing 21.2 mrem/yr After Reduction for Gamma Radiation from Soil

Radionuclide	Dose Factor	Areal Density Equal to 21.2 mrem/yr	
	mrem/yr per pCi/g	pCi/100 cm^2	dpm/100 cm^2
U-238	7.000E-04	1.50E+06	3.33E+06
U-234	5.238E-05	1.82E+07	4.04E+07
U-235	3.487E-03	2.73E+05	6.07E+05
Pa-231	2.928E-03	3.26E+05	7.23E+05
Ac-227	1.376e-02	6.91E+04	1.53E+05

Table 5-4 continued

Radionuclides	Dose Factor	Areal Density Equal to 21.2 mrem/yr	
	mrem/yr per pCi/g	pCi/100 cm^2	dpm/100 cm^2
Th-230	1.561E-04	6.11E+06	1.36E+07
Ra-226	4.825E-02	1.98E+04	4.39E+04
Pb-210	1.269E-03	7.51E+05	1.67E+06
Th-232	1.954E-03	4.88E+05	1.08E+06
Ra-228	1.911E-02	4.99E+04	1.11E+05
Th-228	3.421E-02	2.79E+04	6.18E+04
U nat[b, c]	1.67E-03	5.71E+05	1.27E+06
Th^{230} series[d]	4.97E-02	1.92E+04	4.26E+04
Th-232 +DI[a]	5.527E-02	1.73E+04	3.83E+04

[a] Th-232 +DI is the limit for Th-232 in the situation in which all progeny nuclides are present in equilibrium concentration (*i.e.*, concentration of each equal to the Th-232 concentration). Because Th-232 progeny grows in to equilibrium within about 30 years, and because the C-T facilities have existed for nearly that long, Th-232 progeny can be expected to be near equilibrium.

[b] U nat is the limit for U^{238} , U^{234} , and their short-lived progeny are present in equilibrium and the U^{235} series is present in equilibrium in the proportion occurring in natural uranium.

[c] Radioactivity ratio of U^{235} -to- U^{238} = 0.0455 in natural uranium.

[d] Th^{230} series includes Th^{230}, Ra^{226}, Pb^{210}, and their short-lived progeny in radioactive equilibrium

Radioactive contamination on surfaces is often surveyed by gross activity detection. It is practical, then, to state the contamination limit in units consistent with the measurement. A method of interpreting a surface radioactivity limit and gross beta measurement in comparable units is described in C-T Phase I Decommissioning Plan, Appendix D. The maximum acceptable average areal radioactivity density on a surface, or $DCGL_W$, is expressed in units, pCi/ 100 cm^2, and in units, disintegrations/(min· 100 cm^2) in Table 5-4 for components of the source.

Principal radionuclides in the uranium series, thorium series, and actinium series were measured in 24 samples scabbled on pavement in Plant 5. Lognormal distribution graphics of analytical data, in Table 4-2, indicate that the log mean U_{nat} -to- Th series activity ratio is about 3 -to- 1. Ra^{226} is about 1.5 times more abundant than the $U_{nat.}$ Th^{230} averages about 0.8 of U_{nat} and about 0.6 of Ra^{226}, and for deriving $DCGL_W$, is conservatively be assumed exist in equal radioactivity with Ra^{226}. Applying this distribution to the areal density equal to 21.2 mrem/yr, or $DCGL_W$, in Table 5-4 yields:

$DCGL_W = 6.3 \times 10^4$ dis/(min· 100 cm^2), or
$DCGL_W = 1.8 \times 10^5$ β/(min· 100 cm^2)

The $DCGL_W$ is not very sensitive to radionuclide variability. If, for instance, the source were entirely uranium series in equilibrium, the $DCGL_W$ would = 2.2×10^5 β/(min· 100 cm^2); or if the source were entirely thorium series in equilibrium, the $DCGL_W$ would = 1.4×10^5 β/(min· 100 cm^2). Thus, to enable practical survey by measuring gross beta radiation, $DCGL_W = 1.8 \times 10^5$ β/(min· 100 cm^2) is proposed. Measurement methodology is described in C-T Phase I Decommissioning Plan, Appendix D, §3 "Beta Radiation Measurement."

5.9.2. Area Factor for Elevated Measurements on Pavement

It is desirable to discover any small area of contamination that could cause more than 25 mrem/yr radiological dose. The magnitude by which the concentration within a small area of elevated radioactivity can exceed the $DCGL_w$ while maintaining compliance with the release criterion is defined as an *area factor*.[57] Figure 5-4 provides the *area factor* separately for U series (including actinium series present in natural uranium) , Th series, and a 3 U to 1 Th series mix as a function of a localized area of radioactive contamination on pavement. This is the $DCGL_w$ of each decay series referenced to parent of the series when all progeny are in secular radioactive equilibrium with the parent. The actinium series is assumed present with the uranium series at the radioactivity ratio, U^{235}-to-U^{238} = 0.0455, that occurs naturally.

A composite area factor is calculated as the ratio of composite areal density limits, *i.e.*, DCGL, applicable to U series and Th series combined.

$$\text{Area Factor} = \frac{\text{composite areal DCGL for survey unit area}}{\text{composite areal DCGL for local area of contamination}} \qquad \text{eqn 13}$$

The maximum tolerable areal density of residual radioactive contamination, above background, within a small area of elevated radioactivity is derived by the relation

$$DCGL_{EMC} = \text{Area Factor} \times DCGL_w \qquad \text{eqn 14}$$

where the maximum area factor considered corresponds to 10 m^2 area of elevated contamination. Since the area factors curves in Figure 5-4 are nearly coincident, it is reasonable to adopt the area factor curve representing 3 U series to 1 Th series to apply to the $DCGL_W$ derived in §5.9.1.

Systematically distributed measurements and scanning, together, are employed in each Class 1 survey unit to find such an area of contamination whose areal radioactivity density is elevated above the $DCGL_w$. Measurement of gross beta radiation and interpretation as described in the CT Phase I Decommissioning Plan would be acceptable.

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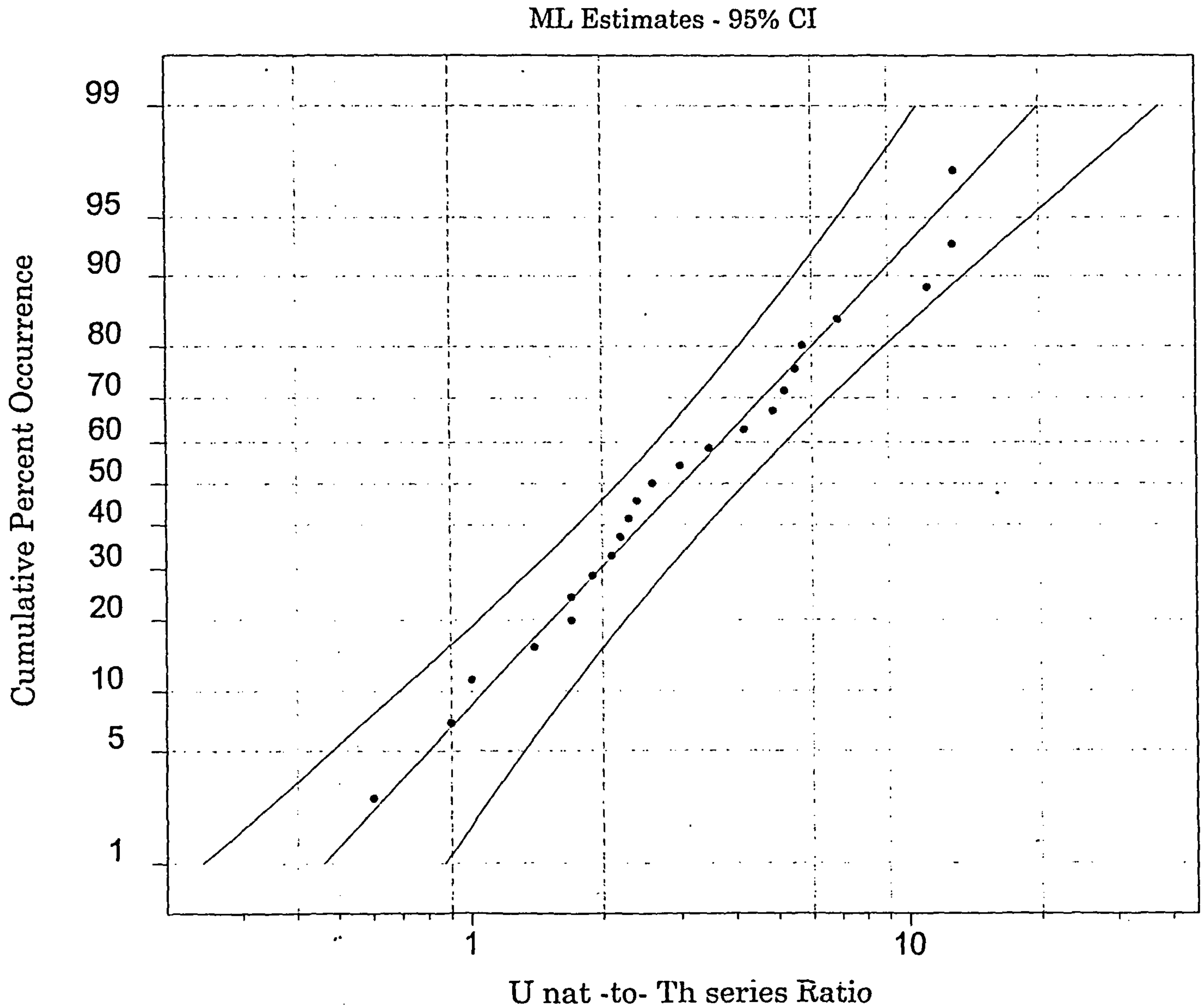
[57] MARSSIM, p. 5-36. Dec. 1997. Biwer, *et.al.* atch C, pp. 7-1 thru 7-4 in NUREG/CR-6697

[58] Composite limit is also referred to as the derived concentration guideline level for the Wilcoxon test ($DCGL_W$).

Distribution of Natural Uranium -to- Thorium Series Ratio in Pavement Scabble Samples



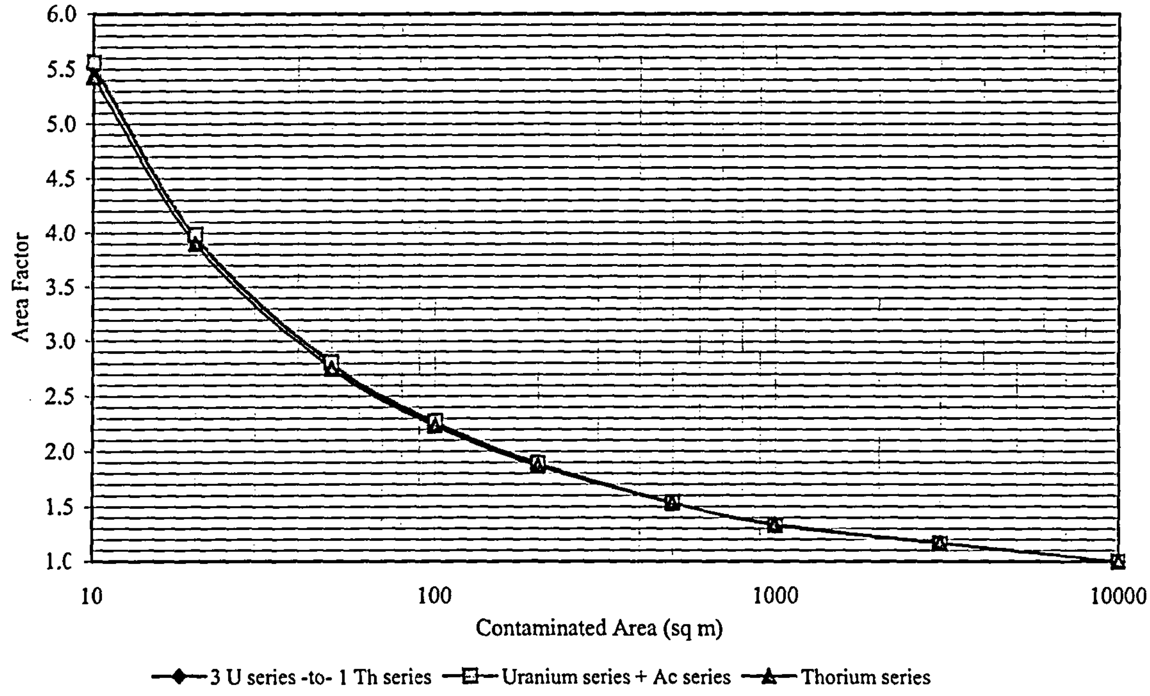


Figure 5-4. Area Factor for Elevated Measurements on Pavement

5.10. SENSITIVITY ANALYSIS

An aim of conceptual and mathematical modeling to derive a DCGL is confidence that the modeling is unlikely to overestimate future radiological dose to an average member of the critical group of people exposed. That confidence is built on conceptual and mathematical simulation in which projected land use scenarios, environmental exposure models, and values of parameters in the models, compounded together, are unlikely to overestimate dose consequence of residual radioactive material.

It is important to understand the effect on dose of values used in the assessment to represent the key parameters. In deterministic modeling,[59] sensitivity analysis calculates the change in the radiological dose, with respect to a small change in the independent variables, one at a time. In a deterministic analysis, it is recognized that the reported dose is one of a range of possible doses that could be calculated for the site. It is important to build confidence that the single reported estimate of the peak dose is likely to be an overestimation of the actual peak dose.

The primary aim of sensitivity analysis is to identify the important assumptions and input

[59] NUREG-1727, Apx. C, §6.3.3, p. C60.

parameters that cause variation in the estimated dose. This helps a modeler to identify conservative land use scenarios, models, and values in order to make a convincing case for the acceptability of the DCGL.

Yu, *et. al.*,[60] have ranked RESRAD input parameters with respect to potential for affecting radiological dose, tendency to vary from site to site, parameter type, and ease of characterization using available literature. The impact on the radiation dose resulting from a change in a parameter value was a major factor in ranking the parameters for analysis.

Ranking of parameters in models used to derive DCGL for soil are in Table 5-5. Parameters ranked Priority 1 were expected to have the greatest potential for affecting radiological dose, tend to vary more from site to site, and are able to be characterized more easily than parameters of lower priority.

Table 5-5. ANL Ranking of Parameters in RESRAD That Are Used to Derive DCGL Herein

Priority 1 (higher)	Priority 2 (mid)	Priority 3 (lower)
Density of cover material *	Nuclide concentration	Time since placement of material*
Density of contaminated zone*	Area of contaminated zone*	Inhalation rate
	Thickness of contaminated zone*	Indoor time fraction
	Cover depth	Outdoor time fraction
	Cover erosion rate	Building foundation thickness*
	Wind speed	Building foundation density*
	Mass loading for inhalation	
	Indoor dust filtration factor	
	External gamma shielding factor	
	Soil ingestion rate* A	
	Depth of soil mixing layer*	

* Default value used for DCGL.

*,A Default value used for industrial worker.

In a particular scenario the sensitivity of derived dose to a change in parameter value depends on the influence of that parameter in each exposure pathway model and on the relative contribution of each pathway to total dose. Some parameters, like radionuclide concentration affect every pathway, whereas other parameters, such as mass loading of airborne dust affect only one or two inhalation pathways.

The Table 5-5 ranking of parameters and the fractional contribution by each pathway to total dose offer an efficient way to judge which are the most influential parameters.

60 Yu, *et. al.*, NUREG/CR-6697. Table 4.2, p. 55.

In the industrial/commercial work scenario, most of potential dose would be caused by gamma irradiation directly from radionuclides in the soil. Minor fractions would be attributable to inadvertent ingestion of soil and inhalation of dust suspended from the soil. Parameters in RESRAD's direct radiation model to which dose is most sensitive to variation would be:

- density of cover material,
- density of contaminated zone,
- nuclide concentration in the contaminated zone,
- area of contaminated zone
- thickness of contaminated zone
- cover depth, and
- external gamma shielding factor while indoors.

Radiological dose by gamma irradiation directly from contaminated soil would be a direct, one-to-one, function of radionuclide concentration in the contaminated zone.

DCGL herein is derived on the basis of the default soil density, 1.5 g/cm^3, in the contaminated zone. Soil density in the contaminated zone does not affect source self-shielding because the contaminated zone is initially assumed to be an infinitely thick source relative to first collision of gamma rays and secondary photon buildup. The thickness of the contaminated zone, assumed to be 2 meters, is effectively an infinitely thick source, given the default soil density. That is, radiological dose would not be increased significantly by increasing the contaminated zone density or diminishing soil density within realistic bounds.

While radiological dose by direct irradiation is a function of the area of the contaminated zone, the 10000 m^2 default area assumed in deriving $DCGL_W$ is effectively infinite in areal extent.

Radiological dose is sensitive to cover depth and density of cover material. Both the industrial/commercial work scenarios assume outdoor exposure to bare, contaminated land, *i.e.*, without cover on the contaminated zone. Whereas, practically all land in Plant 5 is paved or is covered by a concrete slab. Together, they conceptually exclude inhalation and ingestion of contaminated soil and would shield an industrial worker from most direct gamma radiation. If one were to assume 4-inch-thick pavement instead of bare land containing typical 3 parts uranium series -to- 1 part Th series,[61] it would increase the composite $DCGL_W$ derived by RESRAD for an industrial worker about 5 times more than if no pavement were present.

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[61] 3 -to- 1 parts radioactivity (pCi) referenced to parent U^{238} and Th^{232}.

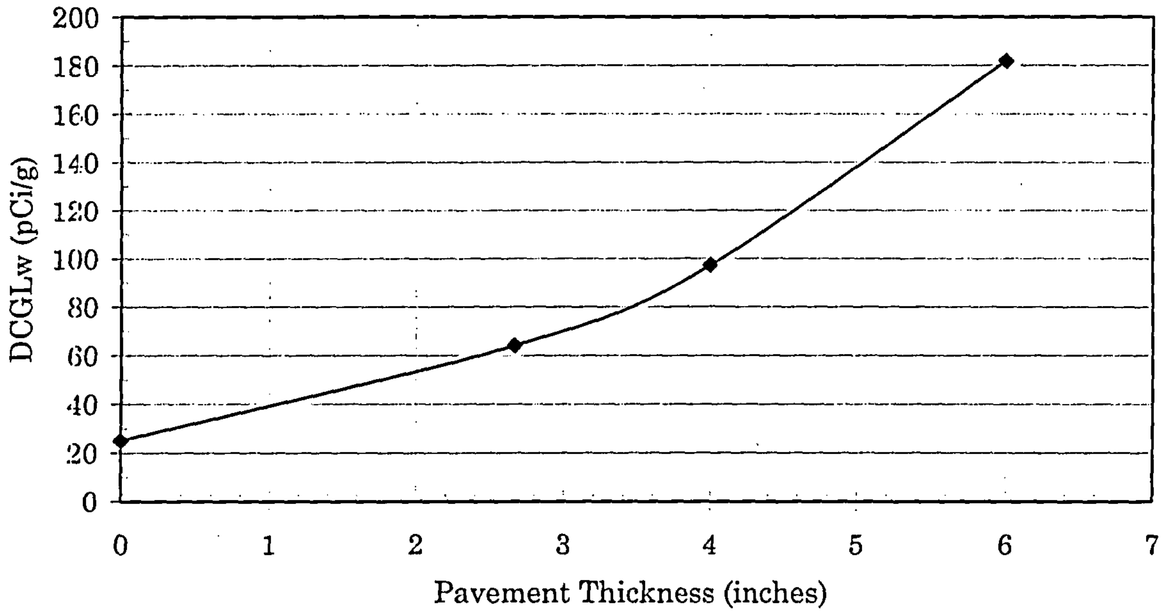

Figure 5-5. Effect of Pavement on DCGLw

Thus, radiological dose would be quite sensitive to depth and density of a pavement cover zone. This is evident in Figure 5-5. Having assumed no pavement when deriving the DCGL in soil tended to overestimate radiological dose and conservatively estimate the $DCGL_W$ in the industrial/commercial scenario herein by a factor of about 5 for typical U series + Th series combined.

5.11. COMPLIANCE WITH REGULATORY CRITERIA

Mallinckrodt proposes to satisfy unrestricted release provisions of 10 CFR Part 20, Subpart E by evaluating final status survey data to demonstrate that

- $DCGL_W$ in §5.8.1.1 and $DCGL_{EMC}$ in §5.8.1.2 are not exceeded in soil affected by C-T operation, and separately that
- $DCGL_W$ in §5.8.3.1 and $DCGL_{EMC}$ in §5.8.3.2 are not exceeded on pavement affected by C-T operations.

Final radiation status survey methods to assess compliance are described in §14, *Facility Radiation Surveys*.

APPENDIX C

PROBABILISTIC DERIVATION OF RADIOLOGICAL DOSE FACTORS AND DCGLw APPLICABLE TO C-T SOIL

1. INTRODUCTION

In its proposed C-T Phase II Decommissioning Plan, Mallinckrodt included a chapter 5, Dose Modeling, describing derivation of radiological dose factors and Derived Concentration Guideline Levels (DCGL). They were derived with the aid of the RESRAD computer code. Commenting on Mallinckrodt's derivation of proposed radiological dose factors and DCGLw applicable to soil, Boby Eid suggested that Mallinckrodt derive them by probabilistic modeling. This report describes such a derivation of dose factors[1] and DCGLw with probabilistic treatment of parameters described in written response to comments by NRC staff.[2]

Derivation of DCGL and assessment of compliance requires integral planning including radionuclides to be measured and tested for compliance. Measurement of key radionuclides by a single method, gamma spectrometry, would be desirable. Otherwise, measurement of Th^{230} would have to be done separately, would be slower than by gamma spectrometry, would introduce additional uncertainty, and would slow remediation prominently. It would be worthwhile to determine conditions and establish specifications under which assessment of compliance can be assured without need to measure Th^{230} routinely during remediation and final status survey. This will involve evaluation of the effect of Th^{230} on radiological dose relative to an associated radionuclide that is measured. Corresponding dose factors from which DCGL are derived are the convenient parameter for analysis.

Another objective will be to explain the methodology of DCGLw derivation and implementation clearly.

2. RADIONUCLIDE SOURCE DISTRIBUTION

Historical assessment and characterization surveys have described the radionuclides of interest and their relative concentrations.[3] Radionuclides include the uranium series, the actinium series in naturally-occurring proportion to the uranium series, and the thorium series. More than 500 soil samples were analyzed for key, long-lived, uranium and thorium series radionuclides during soil characterization survey in Plant 5 . Results are tabulated in CT 2 DP, §4 Radiological Status of Facility.

The ratio of uranium in the U series -to- thorium in the Th series has been observed to be commonly in the range of 2 to 3 in the C-T residual source in Plant 5.

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1 Dose factor = annual radiological dose (mrem/yr) per unit source per gram of soil (pCi/g)

2 Mallinckrodt response items 41 thru 44 to NRC RAI set 1, EPAD Queries.

3 Mallinckrodt C-T Phase II Decommissioning Plan. §4 Radiological Status of Facility.

Relative proportions, or concentrations, of key radionuclides in the U series and in the Th series[4] have been estimated from characterization survey data that are above background.[5] The geometric mean ratios of each distribution of key radionuclides in those data are:

Th-230/U-238 = 1.1
Ra-226/U-238 = 2.8
Ra-228/Th-232 = 1.6
Th-228/Th-232 = 1.3
Th-228/Ra-228 = 0.8
Th-230/Ra226 = 0.66

Uranium Series. As expected, U^{238} and U^{234}, representing the uranium series are measured in approximately equal radioactivity concentration. The actinium series, *i.e.*, U^{235} series, is measured in approximately naturally-occurring proportion to the uranium series. It would be logical to assume U^{238} through U^{234} radionuclides are in radioactive equilibrium and that the actinium series exists in the naturally-occurring ratio to uranium in the uranium series.

Thorium Series. Now, more than fifteen years after cessation of C-T processing, thorium series nuclides are expected to have grown or decayed within about 0.20 of radioactive equilibrium. Considering that C-T feed was ore and that alpha spectrometry of separate radioelements poses some uncertainty at low concentration, the thorium series might rationally be assumed to be in radioactive equilibrium in Plant 5 soil samples. Characterization survey data also suggest an assumption of equilibrium is reasonable. The thorium series will be assumed to be in radioactive equilibrium.

Uranium-to-Thorium. The characterization survey data suggest that a reasonably representative range of source terms would be U -to- Th ratio of approximately 3, with U isotopes in radioactive equilibrium, with Th series in radioactive equilibrium, and with a range of excess Ra^{226}.

Th^{230} -to- Ra^{226}. Among about 600 soil characterization samples collected in Plant 5, more than 500 pairs of Th^{230} and Ra^{226} measurements exist. Among those pairs were 41 pairs containing Th^{230} and Ra^{226} more than 1 standard deviation above mean background concentration. The geometric mean Th^{230} -to- Ra^{226} ratio among those 41 samples is 0.66. Among the 500 pairs, only 3 samples, or 0.006 of samples, exhibit $Th^{230}/Ra^{226} > 6$. Thus, occurrence of Th^{230} -to- Ra^{226} >6 in future sampling would be highly unlikely.

4 Key radionuclides are those radionuclides, each of whose radioactive half-life is greater than 180 days and whose progeny down to the next radionuclide in the series whose radioactive half-life is also greater than 180 days are assumed in secular equilibrium with their parent key radionuclide.

5 Mallinckrodt. CT II DP. apx C.

3. DOSE MODELING

3.1. METHOD

At the suggestion of NRC staff, Boby Eid, probabilistic modeling to derive radiological dose factors and DCGL has been done.

NRC guidance also interprets, "For probabilistic analyses, the peak of the plot of mean dose over time should be compared with the regulatory standard to determine compliance." ... "Essentially a mean dose is determined at each discrete time in the analysis. A plot is then made of these means over time. The mean dose provides the "best estimate" of dose at each discrete time. The overall peak of these best estimates is then used to determine compliance with the rule." [6] With the aid of RESRAD, probabilistic modeling has been done to derive dose factors and DCGL at the *peak of the mean* dose as the guidance suggests.[7]

RESRAD is able to compute and tabulate the time of peak mean dose rate and the peak mean dose rate (mrem/yr). With that information in the probabilistic total dose summary, one can read the contribution by each long-lived radionuclide entered in the source term column corresponding to the time of peak mean dose. The *average (avg)* dose of each source radionuclide at the time of peak mean dose, summed over all of the source radionuclides, equals the peak of the mean dose. Having identified the contribution of each source radionuclide to the peak of the mean total dose, one may derive an appropriate probabilistic dose factor (mrem/yr per pCi/g) as the quotient of the average dose of each source radionuclide at the time of peak mean total dose and the concentration of that radionuclide entered into the source term in RESRAD.

One may derive a composite dose factor for a related series of radionuclides by summing the average dose of each source radionuclide in the series at the time of the peak of the mean dose. Then derive the dose factor as the quotient of that sum and the concentration of the radionuclides to which it is referenced. For example, the composite dose factor of the thorium series would be the sum of doses of the principal radionuclides, including their short-lived progeny, at the time of the peak of the mean dose divided by the initial concentration of the reference, or parent Th^{232}.

Within the range of relative radionuclide concentrations, or spectrum, reasonably expected to be encountered and in question of remediation, the time of peak mean dose was determined by RESRAD probabilistic simulations.

In order to derive the appropriate dose factors, probabilistic simulations were computed across a range of radionuclide source terms encompassing a reasonably representative spectrum of radionuclides expected in Plant 5. Parameters mentioned in §4 herein were described probabilistically.

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6 NRC. *NMSS Decommissioning Standard Review Plan.* NUREG-1727. apx C, §8.3.2.2, p. C116.

7 NUREG-1757, 2, §5.

3.2. PARAMETERS TREATED PROBABILISTICALLY

In an NRC Request for Additional Information (RAI) concerning C-T Phase II DP, set 1, "EPAD Queries," included suggestion that certain variables could be better represented as a variable with a distribution:

- Thickness of the contaminated zone,
- Mass loading for inhalation factor,
- Indoor gamma shielding factor, and
- Occupancy time.

At the same time, EPAD commentary about occupancy time did find Mallinckrodt's proposed allocation of occupancy time to be acceptable.

Mallinckrodt's examination and development of probabilistic distribution of these parameters appears in Mallinckrodt's responses to the NRC RAI set 1. Therein, Mallinckrodt proposed:

- To assume a one-meter-thick contaminated zone,
- A probabilistic distribution of the mass loading for inhalation factor,
- A probabilistic distribution of the indoor gamma shielding factor, and
- 0.2 of 2000 hr/yr out-of-doors onsite and 0.8 of 2000 hr/yr indoors onsite, which EPAD comments found acceptable.

Probability distributions of these variables are discussed in Attachment A.

NRC staff suggested that the probable distribution of indoor concrete thickness include some fraction of thin and of zero thickness concrete. The original distribution has been revised to include some thin and zero thickness concrete, such that now an industrial worker is assumed to be exposed to bare ground 0.24 of exposure time overall and through a 3-inch, thin concrete floor another 0.056 of the time. This is reflected in the probability distribution of indoor gamma shielding factor discussed in Attachment A and illustrated in Figure A3.

A relevant association is that, in plant areas subject to the FUSRAP, with remediation performed by the USACE, radioactivity concentration limit in soil, and radiological dose modeling are being done on the premise that the land will be covered with at least six inches of pavement, gravel, or imported soil, thereby attenuating some of the gamma radiation emanating from soil.

4. COMPLIANCE MODEL

In the uranium series, U^{238} through U^{234} will be assumed to be in radioactive equilibrium and will be represented by measurement of uranium isotope(s) or surrogate progeny. The actinium (U^{235}) series will be assumed to exist in its naturally-occurring proportion to the uranium series.

Radium-226 and its progeny, including Pb^{210}, will be assumed to be in radioactive equilibrium and will be referenced to measured Ra^{226} concentration. Th^{230} will be associated with Ra^{226} and Pb^{210} because the Ra^{226}, to which it decays, presents the dominant dose factor.

Thorium series radionuclides will be assumed to be in radioactive equilibrium and will be represented by measurement of a surrogate radionuclide, Ac^{228}, in the series.

Radiological **dose factors** of individual radionuclides in each subseries may then be composited and stated simply as

$$DF_U = [D(U^{238}) + D(U^{234}) + D(U^{235} + Ac^{227} + Pa^{231})] \div C(U^{238})$$

$$DF_{Ra226\,\&\,Th230} = [D(Ra^{226}) + D(Pb^{210}) + D(Th^{230}{=}6 \cdot Ra^{226})] \div C(Ra^{226})$$

$$DF_{Th\ series} = [D(Th^{232}) + D(Ra^{228}) + D(Th^{228})] \div C(Th^{232})$$

where D_i = annual dose rate of principal radionuclide *ii* and its short-lived progeny at the time of the peak of the mean dose rate posed by the related group of radionuclides (mrem/yr)

C_i = concentration of reference radionuclide *i* in soil (pCi/g soil)

DF = radiological dose factor (mrem/yr)/(pCi/g soil)

Dose factors include long-lived radionuclides mentioned and their short-lived progeny.

The **derived concentration guideline level** may then be stated as

$$DCGL_{W\ U} = \frac{25}{DF_U}$$

$$DCGL_{W\ Ra226} = \frac{25}{DF_{Ra226+Th230}}$$

$$DCGL_{W\ Th\,series} = \frac{25}{DF_{Th\,series}}$$

where 25 = maximum acceptable annual radiological dose (mrem/yr)

$DCGL_W$ = derived concentration guideline level (pCi/g soil)

This permits a simplified statement of the **sum-of-fractions** of the radionuclides encountered in C-T decommissioning to be:

$$SOF = \frac{C_{U238}}{DCGL_{W\,U}} + \frac{C_{Ra226}}{DCGL_{W\,Ra226}} + \frac{C_{Th232}}{DCGL_{W\,Th\ series}}$$

where:

SOF = sum-of-fractions of $DCGL_W$

C_{U238} = concentration of U^{238} in soil (pCi/g)

C_{Ra226} = concentration of Ra^{226} in soil (pCi/g)

C_{Th232} = concentration of Th^{232} in soil (pCi/g)

$DCGL_{W\ U}$ = $DCGL_W$ of U^{238} + U^{234} + actinium (U^{235}) series in its naturally-occurring ratio to the uranium series (pCi/g)

$DCGL_{W\ Ra226}$ = $DCGL_W$ of 6 Th^{230} + Ra^{226} and its progeny, including Pb^{210}, in radioactive equilibrium (pCi/g)

$DCGL_{W\ Th\ series}$ = $DCGL_W$ of Th^{232} and its progeny, including Ra^{228} and Th^{228}, in radioactive equilibrium (pCi/g)

The index, or SOF, determined for each soil sample or location measured, will be the basis of testing compliance with population statistics and elevated measurements criteria.

5. DERIVATION OF THORIUM SERIES DOSE FACTOR AND $DCGL_W$

Thorium series nuclides associated with C-T processing have grown or decayed within about 0.20 of radioactive equilibrium. Considering that C-T feed was ore and that alpha spectrometry of separate radioelements poses some uncertainty at low concentration, the thorium series might rationally be assumed to be in radioactive equilibrium in Plant 5 soil samples. Especially for future estimation, the shorter radioactive half-lives of Ra^{228}, 6.7 yr, and of Th^{228}, 1.9 yr, imply that Th^{232} parent concentration is controlling. Characterization survey data also indicate the thorium series occurs at about a 1/3 of the uranium series concentration in soil.

Assuming the thorium series to be in radioactive equilibrium, a composite dose factor representing the series was derived probabilistically with RESRAD (ref. case 408guti in Attachment C). Equal concentrations of principal radionuclides, Th^{232}, Ra^{228}, and Th^{228}, entered into RESRAD, produce peak of the mean annual dose at year zero and corresponding peak of the mean composite dose factor, DF = 1.05 (mrem/yr)/(pCi Th^{232}/g soil). The corresponding $DCGL_W$ = 23.8 pCi Th^{232}/g soil.

Table 5.1. Thorium Series Dose Factor

Radionuclide	Concentration (pCi/g soil)	Annual Dose Rate (mrem/yr)	Dose Factor (mrem/yr)/(pCi/g)
Ra^{228}	6.248	2.86	
Th^{228}	6.248	3.33	
Th^{232}	6.248	0.348	
	total	6.54	
		composite	1.05

$$DF_{Th\ series} = [D(Th^{232}) + D(Ra^{228}) + D(Th^{228})] \div C(Th^{232})$$
$$= 6.54\ (mrem/yr) \div 6.248\ pCi\ Th^{232}/g\ soil$$
$$= 1.05\ (mrem/yr)/(pCi/g)$$
$$DCGL_{W\ Th\ series} = 25\ mrem/yr \div DF_{Th\ series}$$
$$= 25 \div 1.05 = 23.8\ pCi\ Th^{232}/g\ soil$$

6. DERIVATION OF URANIUM DOSE FACTOR AND $DCGL_W$

Since C-T residue includes natural uranium, it would be logical to consider U^{238} through U^{234} and include the actinium, or U^{235}, series in its naturally-occurring proportion to the uranium series. The principal, or longer-lived radionuclides in the group are

Radionuclide	Proportion
U^{238}	1
U^{234}	1
U^{235}	0.0455
Pa^{231}	0.0455
Ac^{227}	0.0455

When these radionuclides are the source in a RESRAD probabilistic simulation of an industrial land use scenario, the peak of the mean annual dose occurs in the first year of exposure (ref. case 407guti in Attachment C). The composite dose factor,[8] corresponding to the peak of the mean annual dose rate = 0.0347 mrem/yr per pCi U^{238}/g soil. The corresponding $DCGL_W$ = 721 pCi U^{238}/g soil.

Table 6.1. Natural Uranium Dose Factor

Radionuclide	Concentration (pCi/g soil)	Annual Dose Rate (mrem/yr)	Dose Factor (mrem/yr)/(pCi/g)
U^{238}	6.248	7.66×10^{-2}	
U^{234}	6.248	1.79×10^{-2}	
U^{235}	0.2843	1.47×10^{-2}	
Pa^{231}	0.2843	2.97×10^{-2}	
Ac^{227}	0.2843	7.76×10^{-2}	
	total	2.17×10^{-1}	
		composite	3.47×10^{-2}

$$DF_{Th\ series} = [D(U^{238}) + D(U^{234}) + D(U^{235}) + D(Pa^{231} + D(Ac^{227})] \div C(U^{238})$$
$$= 0.217\ (mrem/yr) \div 6.248\ pCi\ U^{238}/g\ soil$$
$$= 3.47 \times 10^{-2}\ (mrem/yr)/(pCi\ U^{238}/g)$$
$$DCGL_{W\ Th\ series} = 25\ mrem/yr \div DF_U$$
$$= 25 \div 3.47 \times 10^{-2} = 721\ pCi\ U^{238}/g\ soil$$

A range of sources, including Th^{230}, Ra^{226}, and the thorium series were also entered into RESRAD along with uranium, and the time of the peak of the mean annual dose including each entire source term was determined. The composite dose factor and $DCGL_W$ representing the uranium nuclide group at the time of the peak of the mean dose caused by the entire source was derived. Results, tabulated in Table 8.2 , demonstrate that the peak of the mean annual dose of a representative range of expected sources predominantly occurs during the first year of exposure. Whenever it occurs during a future year, the derived composite dose factor for uranium is diminished relative to that applicable during the first year of exposure.

Thus, the most conservative composite dose factor and $DCGL_W$ representing uranium at the peak of the mean dose rate it poses are DF = 0.0347 mrem/yr per pCi U^{238}/g soil and $DCGL_W$ = 721 pCi U^{238}/g soil.

8 including all the principal radionuclides and their short-lived progeny

7. DERIVATION OF THE DOSE FACTOR AND DCGLw OF TH^{230} AND RA^{226}

7.1. BASIS

Since Th^{230} transmutes into Ra^{226}, is observed together with Ra^{226} in soil samples, and since the dose factor of Ra^{226} and its progeny, including Pb^{210}, exceed other radionuclides in the uranium series, it is logical to associate Th^{230} and Ra^{226} in dose estimation. Measurement of Th^{230} requires analysis that is slow, expensive, and separate from other key radionuclides. To the extent its presence in excess of uranium or Ra^{226} does not increase potential annual dose substantially and specific measurement is unnecessary, remediation can be done without undue delay.

It would be desirable to adopt a conventional association that does not underestimate potential radiological dose and that allows measured Ra^{226} to represent the subseries. For this reason, it would be logical and useful to link Th^{230} with Ra^{226} in lieu of further measurement of Th^{230} itself.

A subseries beginning with Th^{230} and including Ra^{226}, Pb^{210}, and their short-lived progeny is a logical grouping. In soil, it would be reasonable to assume Ra^{226}, Pb^{210}, and their short-lived progeny are in radioactive equilibrium; although exhalation of Rn^{222} could even leave progeny below equilibrium. The relatively short half-life of Pb^{210}, 21 years, and its lower dose factor than of Ra^{226} justifies compositing the contributions of Ra^{226}, Pb^{210}, and their short-lived progeny to radiological dose.

The sensitivity of Th^{230} contribution to radiological dose and dose factor, particularly within the spectral range of U series and Th series radionuclides present in soil in Plant 5 has been investigated. One goal is to determine the effect of Th^{230} relative to Ra^{226} on influencing radiological dose. What Th^{230} -to- Ra^{226} ratio yields a composite dose factor that does not underestimate the dose from soil samples of C-T residue, and thus DCGLw that assures compliance with the 25 mrem/yr dose criterion? Or, within the range of Th^{230} relative to Ra^{226}, what would be the maximum composite dose factor to represent C-T residue, including Th^{230}, Ra^{226}, Pb^{210}, and their short-lived progeny as a function of increasing Th^{230} -to- Ra^{226}?

7.2. OBSERVED SOURCE

Among about 600 soil characterization samples collected in Plant 5, more than 500 pairs of Th^{230} and Ra^{226} measurements exist. Among those pairs were 41 pairs containing Th^{230} and Ra^{226} more than 1 standard deviation above mean background concentration. The Th^{230}-to-Ra^{226} ratio in these 41 soil samples has a geometric mean value of 0.66. Among those, only 3 samples, or 0.006 of 500 samples, exhibit $Th^{230}/Ra^{226} > 6$. The extensive characterization survey thus indicates that occurrence of Th^{230} -to- $Ra^{226} > 6$ in future soil sampling would be highly unlikely, especially after remediation and that derivation of DF and DCGLw at Th^{230} -to- $Ra^{226} \leq 6$ will assure that the DF is highly unlikely to be underestimated.

7.3. SENSITIVITY ANALYSIS

A series of probabilistic dose modeling was computed with RESRAD in which principal radionuclides, Th^{230}, Ra^{226}, and Pb^{210} were the source. Th^{230} concentration was incremented in excess of Ra^{226} and Pb^{210}. Results are summarized in Table 7.1. Base case 329guti represents Th^{230}, Ra^{226}, Pb^{210}, and their progeny, in radioactive equilibrium, *i.e.*, with Th^{230}/Ra^{226} ratio = 1.

Table 7.1. Dose Factor and DCGLw as a Function of Th^{230}-to-Ra^{226} Ratio

RESRAD Case I.D.	Relative Quantity of Each Radionuclide			Time of Peak of Mean Dose (yr)	$Th^{230} + Ra^{226} + Pb^{210}$	
	Th^{230}	Ra^{226}	Pb^{210}		Dose Factor (mrem/yr)/(pCi/g)	DCGLw (pCi/g)
329guti	1	1	1	0	0.766	32.65
333guti	2	1	1	0	0.772	32.4
335guti	3	1	1	0	0.778	32.1
338guti	4	1	1	0	0.784	31.9
403guti	5	1	1	123	0.811	30.8
399guti	6	1	1	161	0.852	29.4
400guti	8	1	1	239	0.962	26.0
401guti	10	1	1	293	1.08	23.05

Probabilistic mean annual dose as a function of time in the future is displayed graphically and in tabular form in Attachment C for cases in Table 7.1.

Within a population of more than 500 soil characterization samples and among the 41 pairs in which Ra^{226} and Th^{230} are above background mean by more than 1 standard deviation, only 3 samples, or 0.6 %, exhibit Th^{230} -to- $U^{238} > 6$. The peak of the mean dose as a function of increasing Th^{230} -to- the peak of the mean dose when Th^{230} concentration equals Ra^{226} concentration only exceeds 1.1, or increases by as much as 11 percent only when the Th^{230} -to- U^{238} ratio exceeds 6. Adopting the composite dose factor representing Th^{230}, Ra^{226}, Pb^{210}, and their progeny, with Th^{230}/Ra^{226} ratio = 6, would be expected to encompass more than 99% of soil samples.

7.4. RATIO OF PEAK OF MEAN DOSE RATE AT ACTUAL TH^{230} VS $TH^{230} = 6\ RA^{226}$

RESRAD computations were performed to derive radiological dose factors and DCGLw associated with characterization survey samples exhibiting the most excessive Th^{230} and or Ra^{226} concentrations.

Soil characterization survey samples were sorted to select ones in which the ratio of Th^{230}-to-$U_{avg} > 2$ and or Th^{230}-to-$Ra^{226} > 5$, which is > 1 standard deviation above background mean.[9, 10] The most excessive of these sample concentration data, identified in Table 7.2, were entered into RESRAD to compute the probabilistic peak of the mean annual dose rate. A second computation was done for each sample, assuming the Th^{230} concentration equals 6 times the Ra^{226} concentration. Then the ratio of the peak of the mean dose rate at actual Th^{230} concentration -to- the peak of the mean dose rate when Th^{230} concentration is assumed equal to 6 times the Ra^{226} concentration, was derived and is tabulated in Table 7.2.

An objective is to draw conclusion about the significance and boundary condition of assuming Th^{230} to equal 6 times the Ra^{226} concentration when applied to observed radioactivity concentration and extremes of Th^{230} to Ra^{226} concentration. This can be done by deriving the probabilistic peak of mean dose rate at actual Th^{230} concentration and the peak of the mean dose rate when Th^{230} concentration is assumed equal to 6 times the Ra^{226} concentration and comparing the results.

Results of this comparison, in Table 7.2, are that all cases but two demonstrate a peak of the mean dose rate no more than that if Th^{230} were assumed equal to 6 times the Ra^{226} concentration. The exceptions were only 2 and 14 percent greater than when Th^{230} was assumed equal to 6 times the Ra^{226} concentration.

These ratios of peak mean dose rate at actual Th^{230} concentration -to- those when Th^{230} is assumed equal to 6 times the Ra^{226} concentration averages 0.99. In only one anomalous sample was the ratio notably above one. Even in soil samples containing the most excessive concentrations of Th^{230} and Ra^{226}, an assumption that Th^{230} concentration is 6 times the Ra^{226} concentration can be expected to yield a dose factor that will not underestimate radiological dose when applied to practically all soil samples.

Thus, it is reasonable to apply a composite dose factor = 0.852 (mrem/yr)/(pCi Ra^{226}/g soil) and a $DCGL_W$ = 29.4 pCi Ra^{226}/g soil to represent the subseries including Th^{230}, Ra^{226}, and Pb^{210}.

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9 Mallinckrodt. CT II DP. §4, Table 4-7.

10 Mallinckrodt. CT II DP, apx. C, Table C-1.

Table 7.2. Dose Estimation for Soil Characterization Samples Containing Excess Th^{230} and or Ra^{226}

RESRAD Case I.D.	Sample Identification		Th^{230} to U_{avg} ratio	Th^{230} to Ra^{226} ratio	Ra^{226} to U_{avg} ratio	Time to Peak of Mean (yr)	Peak of Mean Dose Rate (mrem/yr)	Ratio of Peak of Mean Dose Rate at actual Th^{230} vs Th^{230} = 6 Ra^{226}
	Location	Depth at Bottom (ft)						
348bh11	BH-011	3.5	101.	2.07	48.9	0	124.7	0.978
409guti	BH-011	3.5	293.	6	48.9	0	127.5	
349bh22	BH-022	5.5	1.53	5.84	0.26	0	10.14	0.999
410bh22	BH-022	5.5	1.57	6.0	0.26	0	10.15	
353bh09	BH-009	2.5	7.6	1.7	4.5	0	19.04	0.976
411bh09	BH-009	2.5	26.8	6.0	4.5	0	19.47	
355bh10	BH-010	2.5	12.7	0.91	11.6	0	252.1	0.972
412bh10	BH-010	2.5	69.6	6.0	11.6	0	259.3	
357bh12	BH-012	5.5	2.39	0.097	24.6	0	229.2	0.949
413bh12	BH-012	5.5	148.	6.0	24.6	125	241.6	
359bh15	BH-015	5.5	6.33	0.302	21.0	0	291.5	0.944
414bh15	BH-015	5.5	126.	6.0	21.0	125	308.9	
361bh15a	BH-015A	9.5	3.7	0.352	10.6	0	673.9	0.947
415bh15a	BH-015A	9.5	63.4	6.0	10.6	125	711.4	
363bh38	BH-038	1.0	2.46	8.30	0.30	125	21.31	1.02
416bh38	BH-038	1.0	1.77	6.0	0.30	0	20.93	
365bh38	BH-038	6.5	2.22	5.90	0.38	0	4.701	1.00
417bh38	BH-038	6.5	2.26	6.0	0.38	0	4.703	
367bh41	BH-041	3.5	3.69	10.4	0.35	244	7.841	1.136
418bh41	BH-041	3.5	2.13	6.0	0.35	0	6.901	
369bh42	BH-042	1.0	3.01	6.40	0.47	0	6.119	1.00
419bh42	BH-042	1.0	2.83	6.0	0.47	0	6.107	
371ja04	JA-04	1.0	2.38	0.60	3.97	0	111.1	0.932
420ja04	JA-04	1.0	1.0	6.0	3.97	159	119.2	

8. DERIVATION OF DOSE FACTORS AND DCGLw IN A RANGE OF SOURCE TERMS

Radiological dose factors may be demonstrated applicable over a wide range of source distribution encompassing C-T residue in soil. Source terms including: a) 2 U series -to- 1 Th series and 3 U series -to- 1 Th series, most representative in C-T samples, b) a range of excess Ra^{226} and Pb^{210}, and c) a range of excess Th^{230} were subject to simulation with RESRAD. From these separate cases and source terms, identified in Table 8.1, composite dose factors and DCGLw were derived.

Table 8.1. Composite Dose Factor and DCGLw Derived Separately

Radionuclide Group	Composite Dose Factor[11] (mrem/yr)/(pCi/g)	DCGLw[20] (pCi/g)	RESRAD case
Th series	1.05	23.9	408guti
Natural Uranium	0.0347	721.	407guti
6 Th^{230} + Ra^{226} + Pb^{210}	0.852	29.4	399guti

Evident in these simulations are that:

- Dose factors and DCGLw derived separately for natural uranium and for the thorium series (ref. Tables 5.1, 6.1, 7.1, and 8.1) agree closely with the dose factors and DCGLw in Table 8.2.
- When the Th^{230} -to- Ra^{226} ratio is ≤ 6, dose factors are lower and DCGLw are higher than when derived separately for 6 Th^{230} + Ra^{226} + Pb^{210}.

Thus, over a wide range, encompassing the C-T source distribution in soil, the derived dose factor and DCGLw proposed for natural uranium and the thorium series are representative, and for Th^{230} + Ra^{226} + Pb^{210}, overestimates the dose. Only if the Th^{230} -to- Ra^{226} ratio were > 6 could the Ra^{226} dose be underestimated; yet the occurrence of that was very low, < 0.01, in characterization survey measurements.

[11] DF and DCGLw are referenced to Th^{232}, U^{238}, and Ra^{226} respectively.

Table 8.2. Composite Dose Factor and DCGLw Derived in a Range of Source Distribution

RESRAD case	Relative Concentration of Key Radionuclide in Soil				Time of Peak of Mean Dose (yr)	Natural Uranium: U238, U234, + U235 series		Th^{230} + Ra^{226} + Pb^{210}		Thorium series	
	U series	Th series	Excess Ra226	Excess Th230		Dose Factor (mrem/yr)/(pCi/g	DCGLw (pCi/g)	Dose Factor (mrem/yr)/(pCi/g	DCGLw (pCi/g)	Dose Factor (mrem/yr)/(pCi/g	DCGLw (pCi/g)
301guti	3	1	0	1	0	3.47E-02	7.21E+02	7.73E-01	3.23E+01	1.05E+00	2.39E+01
302guti	3	1	0	2	0	3.47E-02	7.21E+02	7.75E-01	3.23E+01	1.05E+00	2.39E+01
303guti	3	1	0	3	0	3.47E-02	7.21E+02	7.77E-01	3.22E+01	1.05E+00	2.39E+01
304guti	3	1	0	4	0	3.47E-02	7.21E+02	7.79E-01	3.21E+01	1.05E+00	2.39E+01
305guti	3	1	0	6	0	3.47E-02	7.21E+02	7.83E-01	3.19E+01	1.05E+00	2.39E+01
384guti	3	1	0	8	0	3.47E-02	7.21E+02	7.87E-01	3.18E+01	1.05E+00	2.39E+01
385guti	3	1	0	10	0	3.47E-02	7.21E+02	7.91E-01	3.16E+01	1.05E+00	2.39E+01
388guti	3	1	0	27	234	1.51E-02	1.66E+03	1.08E+00	2.31E+01	7.30E-01	3.43E+01
307guti	3	1	1	1	0	3.47E-02	7.21E+02	7.70E-01	3.25E+01	1.05E+00	2.39E+01
308guti	3	1	2	2	0	3.47E-02	7.21E+02	7.69E-01	3.25E+01	1.05E+00	2.39E+01
309guti	3	1	4	4	0	3.47E-02	7.21E+02	7.68E-01	3.25E+01	1.05E+00	2.39E+01
310guti	3	1	6	6	0	3.47E-02	7.21E+02	7.70E-01	3.25E+01	1.05E+00	2.39E+01
311guti	3	1	2	1	0	3.47E-02	7.21E+02	7.68E-01	3.26E+01	1.05E+00	2.39E+01
312guti	3	1	4	1	0	3.47E-02	7.21E+02	7.66E-01	3.27E+01	1.05E+00	2.39E+01
313guti	3	1	6	1	0	3.47E-02	7.21E+02	7.66E-01	3.26E+01	1.05E+00	2.39E+01
314guti	3	1	1	2	0	3.47E-02	7.21E+02	7.72E-01	3.24E+01	1.05E+00	2.39E+01
315guti	3	1	4	2	0	3.47E-02	7.21E+02	7.66E-01	3.26E+01	1.05E+00	2.39E+01
316guti	3	1	6	2	0	3.47E-02	7.21E+02	7.67E-01	3.26E+01	1.05E+00	2.39E+01
317guti	3	1	3	1	0	3.47E-02	7.21E+02	7.73E-01	3.23E+01	1.05E+00	2.39E+01
318guti	3	1	2	3	0	3.47E-02	7.21E+02	7.70E-01	3.24E+01	1.05E+00	2.39E+01
319guti	3	1	3	3	0	3.47E-02	7.21E+02	7.69E-01	3.25E+01	1.05E+00	2.39E+01
320guti	3	1	4	3	0	3.47E-02	7.21E+02	7.67E-01	3.26E+01	1.05E+00	2.39E+01
321guti	3	1	6	3	0	3.47E-02	7.21E+02	7.68E-01	3.26E+01	1.05E+00	2.39E+01
322guti	3	1	1	4	0	3.47E-02	7.21E+02	7.75E-01	3.23E+01	1.05E+00	2.39E+01
323guti	3	1	2	4	0	3.47E-02	7.21E+02	7.72E-01	3.24E+01	1.05E+00	2.39E+01
324guti	3	1	6	4	0	3.47E-02	7.21E+02	7.68E-01	3.25E+01	1.05E+00	2.39E+01
325guti	3	1	1	6	0	3.47E-02	7.21E+02	7.78E-01	3.21E+01	1.05E+00	2.39E+01
326guti	3	1	2	6	0	3.47E-02	7.21E+02	7.74E-01	3.23E+01	1.05E+00	2.39E+01
327guti	3	1	3	6	0	3.47E-02	7.21E+02	7.72E-01	3.24E+01	1.05E+00	2.39E+01

RESRAD case	Relative Concentration				Time of Peak of Mean Dose (yr)	Natural Uranium		$Th^{230} + Ra^{226} + Pb^{210}$		Thorium series	
	U series	Th series	Excess Ra^{226}	Excess Th^{230}		Dose Factor (mrem/yr)/(pCi/g	$DCGL_W$ (pCi/g)	Dose Factor (mrem/yr)/(pCi/g	$DCGL_W$ (pCi/g)	Dose Factor (mrem/yr)/(pCi/g	$DCGL_W$ (pCi/g)
328guti	3	1	4	6	0	3.47E-02	7.21E+02	7.70E-01	3.25E+01	1.05E+00	2.39E+01
340guti	3	1	0	0	0	3.46E-02	7.23E+02	7.66E-01	3.27E+01	1.04E+00	2.40E+01
341guti	2	1	0	1	0	3.46E-02	7.22E+02	7.69E-01	3.25E+01	1.04E+00	2.40E+01
342guti	2	1	0	2	0	3.46E-02	7.22E+02	7.72E-01	3.24E+01	1.04E+00	2.40E+01
343guti	2	1	0	4	0	3.46E-02	7.22E+02	7.78E-01	3.21E+01	1.04E+00	2.40E+01
344guti	2	1	0	6	0	3.46E-02	7.22E+02	7.84E-01	3.19E+01	1.04E+00	2.40E+01
386guti	2	1	0	10	0	3.46E-02	7.22E+02	7.97E-01	3.14E+01	1.04E+00	2.40E+01
387guti	2	1	0	18	186	1.72E-02	5.42E+03	1.05E+00	2.38E+01	7.71E-01	3.24E+01
345guti	2	1	1	1	0	3.46E-02	7.22E+02	7.66E-01	3.26E+01	1.04E+00	2.40E+01
346guti	2	1	1	2	0	3.46E-02	7.22E+02	7.68E-01	3.26E+01	1.04E+00	2.40E+01
375guti	1	0	0	0	0	3.46E-02	7.23E+02	7.71E-01	3.24E+01	-	-
402guti	1 U238 + 1 U234 + 0.0455 U235 + 0.0455 Ac227 + 0.0455 Pa231)				0	3.47E-02	7.21E+02	-	-	-	-

Natural uranium dose factor and DCGLw referenced per pCi parent U238/g soil

Th230 + Ra226 + Pb210 dose factor and DCGLw referenced per pCi Ra226/g soil

Th series dose factor and DCGLw referenced per pCi Th232/g soil

9. APPLICATION OF DERIVED DOSE FACTORS

Whether the proposed compositing of dose factors to enable practical measurement of radionuclides during remediation and final status survey is reasonable was tested by calculating in two ways the potential radiological dose associated with soil samples containing Th^{230} and Ra^{226} above background and maximal Th^{230}-to-Ra^{226} ratio. Soil characterization survey samples were sorted to select ones in which Th^{230} and Ra^{226} are above background mean by more than one standard deviation. Results are in Attachment B. In only 3 samples was the ratio of Th^{230}-to-Ra^{226} > 6 and was > 5 in only two more.

Results of dose estimates by RESRAD and by the composite dose factors are tabulated.

Table 9.1. Estimates of Radiological Dose by RESRAD and by Composite Dose Factors

Soil Sample		Radionuclide Concentration[A]			Th^{230}/Ra^{226}	Radiological Dose	
Location	Depth to bottom (ft)	U^{238} (pCi/g)	Ra^{226} (pCi/g)	Th^{232} (pCi/g)	ratio	by RESRAD (mrem/yr)	by Composite Dose Factors (mrem/yr)
BH-022	5.5	35.5	9.3	1.6	5.8	10.2	10.8
BH-038	1	56.4	16.7	5.3	8.3	21.3	21.8
BH-041	3.5	16.65	5.9	1.47	10.4	7.8	7.2
BH-042	1	10.6	5.0	1.7	6.4	6.1	6.4
BH-114	4	34.8	5.6	1.11	5.4	6.7	7.1

[A] U^{238} represents average of U^{238} and U^{234} analyses
Ra^{226} represents Ra^{226}.
Th^{232} represents average of Th^{232}, Ra^{228}, and Th^{228} analyses.

The composite radiological dose factors for this table include dose from concentrations in soil of

- U^{238}, U^{234}, and U^{235} series in natural proportion per pCi U^{238}/g soil;
- Th^{230}, Ra^{226}, and Pb^{210} where Th^{230} = 6 times Ra^{226} and Pb^{210} = Ra^{226}, referenced per pCi Ra^{226}/g and
- Thorium series in radioactive equilibrium, referenced per pCi Th^{232} per g.

Radiological dose rate employing the composite dose factors was estimated with the equation:

$$\text{Dose Rate} = (C \times DF)_{U^{238}\text{ thru }U^{234}} + (C \times DF)_{Th^{230}+Ra^{226}} + (C \times DF)_{Th\text{ series}}$$

where: C_i = radioactivity concentration of U^{238}, representing average of U^{238} and U^{234} (pCi/g); of Ra^{226}, representing Ra^{226}, and of Th^{232}, representing the average of Th^{232}, Ra^{228}, and Th^{228} (pCi/g)

DF_i = composite radiological dose factor (mrem/yr)/(pCi/g)

In these instances of maximum observed Th^{230} -to- Ra^{226} ratio, dose estimates by RESRAD and by the composite dose factors are nearly the same. $DCGL_W$ derived with these same composite dose factors would, likewise, be appropriate to ensure compliance when U^{238}, Ra^{226}, and Th^{232} are measured.

Even if the Th^{230} -to- Ra^{226} ratio were somewhat higher than 6 in one or two instances after remediation to remove substantially contaminated soil, the peak of the mean dose would remain below the elevated measurement criterion and would be tolerable even if underestimated on the basis of a DCGL derived when Th^{230} concentration is assumed equal to the U^{238} concentration.

10. MEASUREMENT

Properties of the residual radioactive source observed during characterization surveys have enabled the radioactive properties and range of the source term expected to remain after remediation to be estimated.

The thorium series will be assumed to be in radioactive equilibrium. One or more surrogate radionuclides such as Ac^{228} and or Tl^{208} may be measured as surrogate(s) to represent the concentration of key radionuclides and thus the thorium series.

Either uranium isotope(s) may be measured during final status survey or surrogate progeny may be measured to represent the parent uranium. Considering characterization survey data, the U^{238} and U^{234} will be assumed to be in radioactive equilibrium, *i.e.*, equal radioactivity concentration, together with the actinium (U^{235}) series in its naturally-occurring ratio.

Radium-226 may be measured, either directly and or by surrogate progeny to represent Ra^{226}.

Characterization survey measurements (ref. CT 2 DP, Tables 4-7 thru 4-16), and Attachment B, herein, indicate that Th^{230} is unlikely to be more than 6 times the Ra^{226} concentration above background. Probabilistic dose calculations have determined that, within the reasonably expected distribution, i.e., spectra, of key radionuclides in soil, Th^{230} may be grouped with its progeny, Ra^{226}. Thus, the subseries of Th^{230}, Ra^{226}, and Pb^{210}, and their short-lived progeny will be represented by measuring Ra^{226} and or surrogate progeny to represent it.

The radiological dose is very unlikely to be underestimated when combined dose factors include 1) U^{234} and U^{238} in equal concentration, 2) U^{235} series in radioactive equilibrium existing in naturally-occurring proportion to U^{238}, 3) Th230 assumed to exist in 6 times the concentration of Ra^{226}, and 4) the thorium series is assumed in radioactive equilibrium.

ATTACHMENT A

DOSE MODELING PARAMETERS SIMULATED PROBABILISTICALLY

THICKNESS OF THE CONTAMINATED ZONE

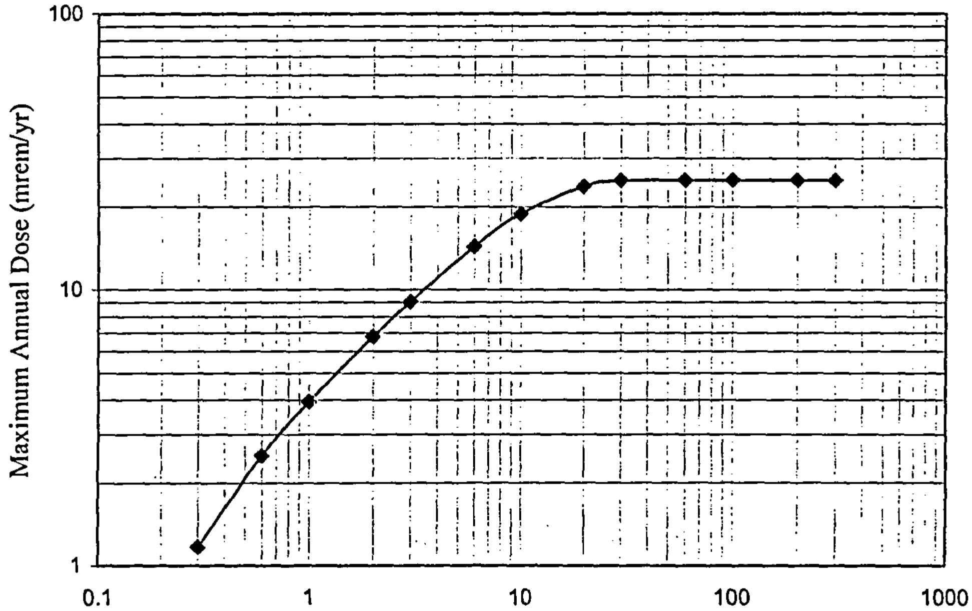
In response to the RAI set 1 EPAD comment about thickness of the contaminated zone, it was demonstrated that assuming greater than a one-meter-thick contamination depth in soil would not cause additional dose, increase the dose factor, nor diminish the DCGL. The thickness of the contaminated zone is the depth distance between the uppermost and lowermost soil samples that have radionuclide concentration above background. Whereas, in deterministic modeling, a one-meter-thick depth of contaminated soil was modeled, in probabilistic modeling, Mallinckrodt proposes a uniform distribution ranging from 0 to 1 meter.

<u>Probabilistic</u>. An analysis of the effect of contaminated zone thickness on radiological dose during industrial land use was done to interpret the depth beyond which additional contribution from a representative source in soil to irradiation dose to a person would become negligible. Essential features of modeling to perform this analysis were:

- a reasonably representative source ratio of 3 U series, 0.0455 x 3 actinide (U^{235}) series, and 1 Th series together.
- bare land in which residual source contamination extends from land surface downward into the soil;
- indoor time fraction = 0.0 in order to simulate effect of irradiation on bare land;
- the same industrial land use scenario modeled to derive DCGLw originally, except absent ingestion of soil and inhalation of dust; (for the origin of inadvertently ingested dust and of dust suspended into air is surficial topsoil); and
- deterministic simulation using RESRAD to derive the effect of increasing contamination depth in soil on exposure to direct irradiation.

The result of this analysis is summarized graphically in Figure A1. It determined that, in representative simulation, maximum dose rate by direct irradiation is reached asymptotically when the depth of the contaminated zone in topsoil reaches about 30 cm. Additional source thickness would not produce significantly greater dose rate.

Figure A1. Maximum Annual Radiological Dose Versus Source Depth in Soil
(infinitely-thick source ratio 3 U series + 1 Th series produces 25 mrem/yr)



As a result of this analysis, the thickness of contaminated zone parameter will be represented as a variable in probabilistic dose modeling. It is being represented as a uniform distribution ranging from 0 to 1 meter thick since characterization survey soil sampling intervals are insufficient to resolve a well-defined gradient within this range. A maximum depth of 1 meter is more than sufficient to be a conservative representation insofar as direct irradiation is concerned.

MASS LOADING FOR INHALATION

Estimation of intake by inhalation depends on the airborne concentration of contaminated airborne particulate matter, *i.e.*, soil, that is respirable. Respirable particles are those less than 10 µm in diameter. About 0.28 to 0.33 of airborne particles have been found to be respirable.[12, 13, 14, 15] The mass loading of respirable particulate in air may be

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12 USEPA. *Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment.* EPA 520/4-77-016. pp. 31-32. Sept. 1977.

13 Chepil, W.S., "Sedimentary Characteristics of Dust Storms: III Composition of Suspended Dust." Am. J. Sci., 225, p. 206, 1957. in EPA 520/4-77-016, p. 57

14 Sehmel, G.A., *Radioactive Particle Resuspension Research Experiments on the Hanford Reservation*, BNWL-2081, 1977.

15 Willeke, K. *et.al.*, "Size Distribution of Denver Aerosols - A Comparison of Two Sites," Atm. Env., 8, p. 609, 1974.

estimated as the product of the total mass loading of airborne dust and the respirable fraction.

Deterministic. The total mass loading of airborne dust in an urban area has been estimated to range from 60 to 220 μg/m³ by USHEW[16] and 33 to 254 by Gilbert, *et.al.*[17] A best geometric estimate is about 115 μg/m³. Thus, a reasonable estimate of respirable mass loading for inhalation in an urban, industrial area is 0.3 x 115 μg/m³ = 35 μg/m³. (This is about the upper 90th percentile recommended for use in RESRAD in a residential environment.[18] Long-term measurements of mass loading in ambient air are 23 μg/m³ at the 50th percentile.)

Probabilistic. The model of radionuclides in outdoor air subject to inhalation is the product of the radionuclide concentration in surface soil and the airborne density of particulates of respirable size in ambient air. Biwer, *et.al.*,[19] summarized the distribution of respirable particulate in ambient air reported by the EPA[20] for about 1790 air monitoring stations in a range of environments. At cumulative probability = 0.50, the most frequent respirable particulate density in the EPA distribution occurs at about 23 μg/m³ air.[21]

Three other sources of data were examined to get more comprehensive information about airborne particulate density in urban air. The total mass loading of airborne dust in an urban area has been estimated to range from 60 to 220 μg/m³ by USHEW[22] and 33 to 254 by Gilbert, *et.al.*[23] Their respective geometric means are approximately 115 and 92 μg/m³. Airborne particulates measured in 14494 urban and 3114 non-urban air samples in the National Air Sampling Network exhibited a geometric mean of 98 μg/m³.[24] A best geometric estimate of those is about 102 μg/m³.

Estimation of intake by inhalation depends on the airborne concentration of contaminated airborne particulate matter, *i.e.*, soil, that is respirable. About 0.28 to 0.38 of

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16 USHEW. *Air Quality Criteria for Particulate Matter.* 1969. in NUREG/CR-5512, 1, p. 6.11.

17 Gilbert, T.L., *et.al.*, *Pathways Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites.* ORO-832 rev. Jan 1984. in Yu, C. *et.al.*, *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. pp. 110-111, Apr. 1983.

18 Biwer, *et.al.* atch C, p. c4-16 in NUREG/CR-6697.

19 Biwer, *et.al.* "Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes." atch C, pp. C4-15 & C4-16 in NUREG/CR-6697. Dec. 2000.

20 USEPA. Aerometric Information Retrieval System. internet site http://www.epa.gov/airs/airs.html. 1999.

21 Biwer, *et.al.*, Table 4.6-1 and Fig. 4.6-1 in NUREG/CR-6697.

22 USHEW. *Air Quality Criteria for Particulate Matter.* 1969. in NUREG/CR-5512, 1, p. 6.11.

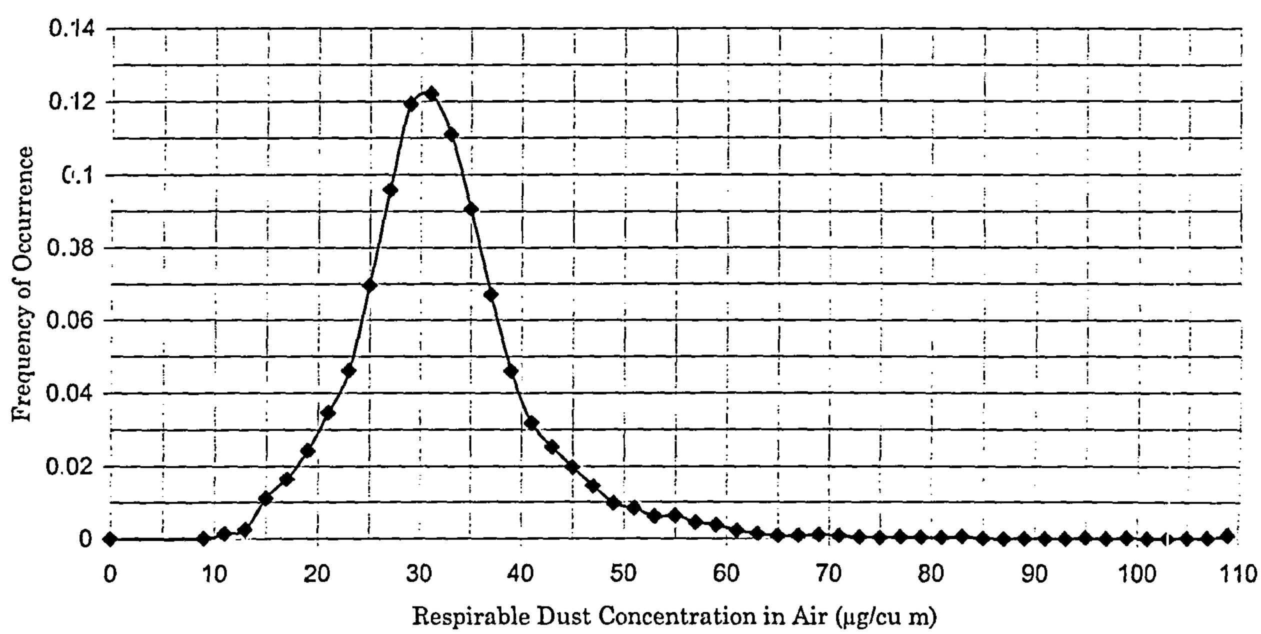
23 Gilbert, T.L., *et.al.*, *Pathways Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites.* ORO-832 rev. Jan 1984. in Yu, C. *et.al.*, *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. pp. 110-111, Apr. 1983.

24 Stern, A.C., ed. *Air Pollution.* 2nd ed. Academic Press. NY. 1968.

airborne particles have been found to be respirable, *i.e.*, less than 10 μm in diameter.[25, 26, 27, 28] The mass loading of respirable particulate in air may be estimated as the product of the total mass loading of airborne dust and the respirable fraction. Thus, a reasonable estimate of the geometric mean of respirable mass loading for inhalation in an urban, industrial area is about 0.3 x 102 $\mu g/m^3$ = 31 $\mu g/m^3$.

A distribution representing airborne particulate loading in urban air may be estimated by the shape of the distribution in NUREG/CR-6697, Table 4.6-1 and shifted upward by an increment representing the increase in dust in urban air relative to all ambient air. The result, in Figure A2, becomes the probabilistic distribution to replace the default distribution in RESRAD v. 6.22. This distribution represents careful, reasonable appraisal of values of airborne mass loading in an urban environment.

Figure A2. Frequency Distribution of Respirable Dust in Urban Air
(EPA AIRS PM-10 data normalized to urban environment)



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[25] USEPA. *Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment.* EPA 520/4-77-016. pp. 31-32. Sept. 1977.

[26] Chepil, W.S., "Sedimentary Characteristics of Dust Storms: III Composition of Suspended Dust." Am. J. Sci., 225, p. 206, 1957. in EPA 520/4-77-016, p. 57

[27] Sehmel, G.A., *Radioactive Particle Resuspension Research Experiments on the Hanford Reservation*, BNWL-2081, 1977.

[28] Willeke, K. *et.al.*, "Size Distribution of Denver Aerosols - A Comparison of Two Sites," Atm. Env., 8, p. 609, 1974.

It is represented in RESRAD as a continuous linear distribution with entries in Table A1.

Table A1. Respirable Particulate in Urban Air

Respirable Particulate Concentration (μg/m³)	Frequency
0.	0.0
15.	0.0151
23.	0.1365
37.	0.8119
47.	0.9495
67.	0.9937
83.	0.9983
107.	0.9992

GAMMA SHIELDING FACTOR

The gamma shielding factor indoors has been revised to treat it probabilistically and to assume a fractional occurrence on bare ground and a thin floor. Table A2 describes the discrete cumulative probability distribution simulating the external gamma shielding factor applicable indoors.

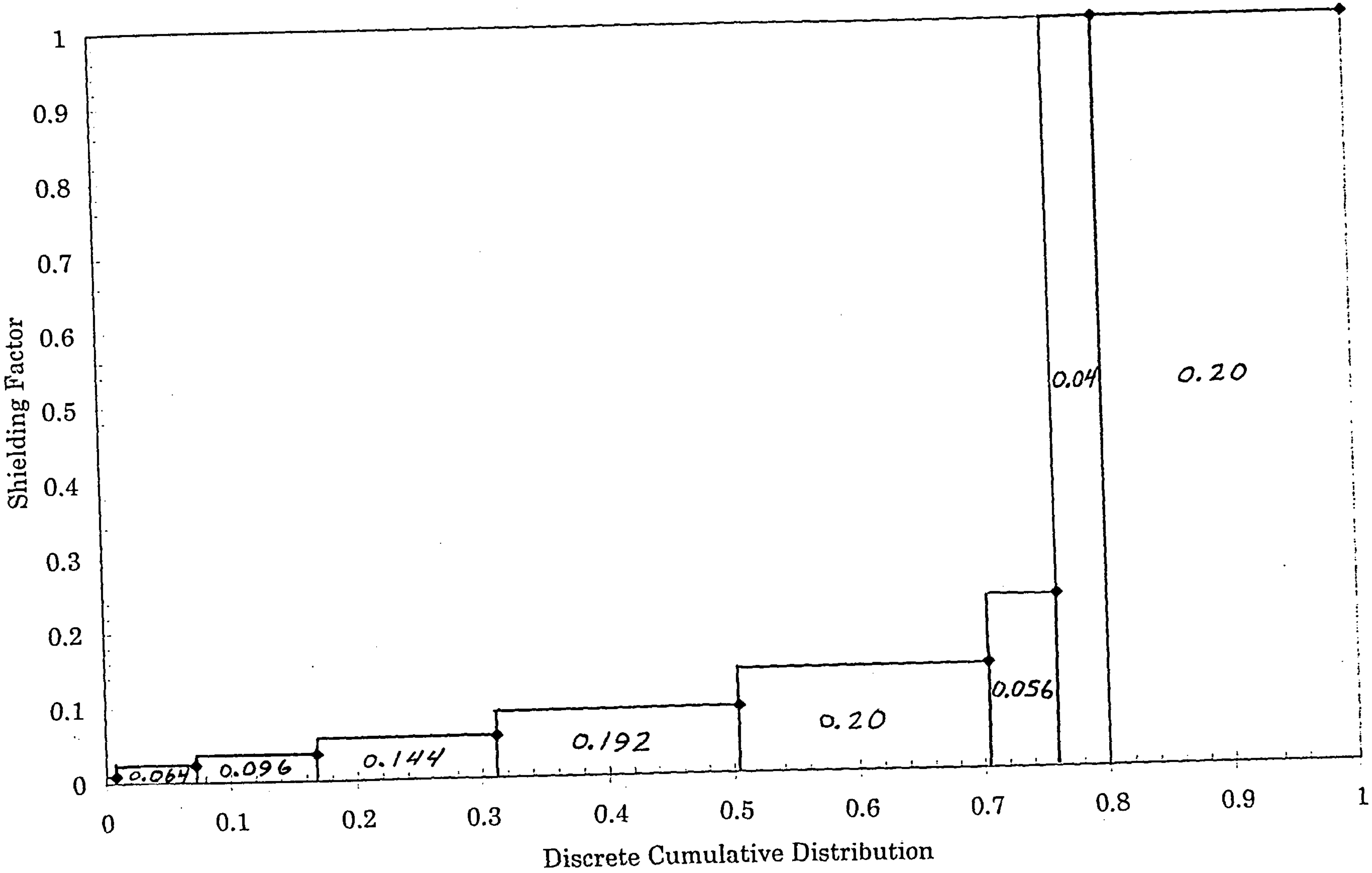
Table A2. Gamma Shielding Factor Distribution

Location	Shielding Thickness (in)	Shielding Factor ("value")	Fractional Occurrence	Cumulative Distribution Indoor Only (cdf)
indoor	10	0.0084	0.01	0.01
indoor	8	0.022	0.08	0.09
indoor	7	0.035	0.12	0.21
indoor	6	0.055	0.18	0.39
indoor	5	0.088	0.24	0.63
indoor	4	0.14	0.25	0.88
indoor	3	0.23	0.07	0.95
indoor	0	1.0	0.05	1.0
outdoor	0	1.0	0.20	

Occupancy 20% of the time on bare ground, with gamma shielding factor = 1.0, is, in addition, assumed to apply deterministically while out-of-doors, even though most of Plant 5 is paved. Overall, then, dose modeling has been adjusted to simulate a person on bare ground about 24% of their time while on-site and thin shielding an additional 5.6% of the time. This is illustrated diagrammatically in Figure C3.

A relevant association is that, on the area of the site that is subject to the FUSRAP, the USACE remediation and dose modeling are based on a premise that the land will be covered by at least six inches of pavement, gravel, or unaffected fill.

Figure C3. Cumulative Distribution of Indoor and Outdoor Shielding Fraction



ATTACHMENT B

THORIUM-230 -TO- RADIUM-226 RATIO IN SOIL CHARACTERIZATION SAMPLES

Soil characterization survey samples were sorted to select ones in which Th^{230} and Ra^{226} are above background mean by more than one standard deviation. Among more than 500 samples were 41 qualifying samples. Among these 41 samples, the Th^{230}-to-Ra^{226} ratio exceeded 6 in only 3 samples and exceeded 5 in only 2 more.

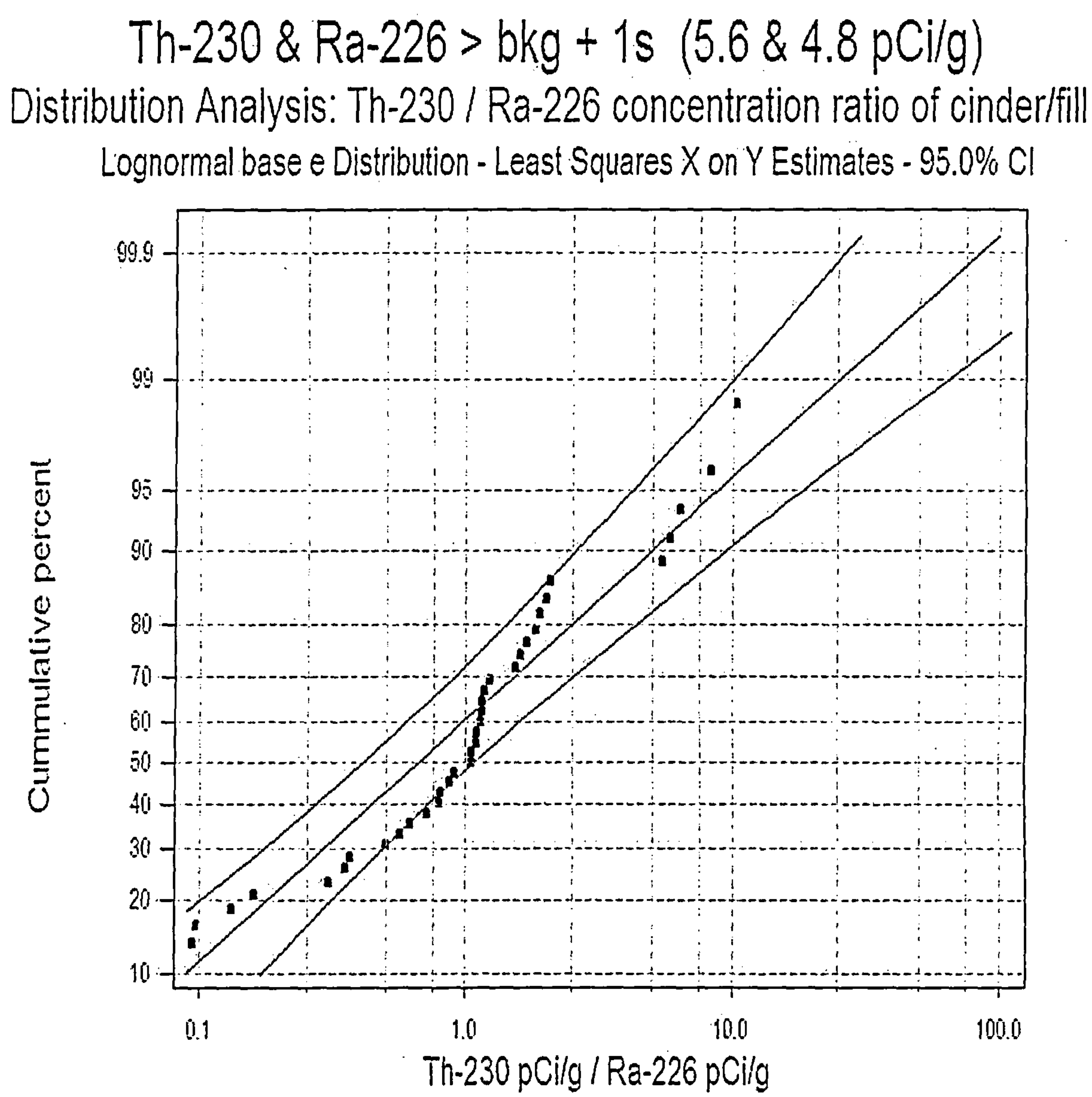


Figure B1. Th^{230} -to- Ra^{226} Ratio in Soil Characterization Samples

Table B1. C-T Soil Characterization Survey Data in which Ra-226 and Th-230 Concentrations are More than One Standard Deviation above Natural Background Mean

Location ID	Sample Depth (ft)		Radionuclide Concentration		Ratio
	Top	Bottom	Th-230 (pCi/g)	Ra-226 (pCi/g)	Th-230 / Ra-226
BH-009		2.5	27.6	16.3	1.7
BH-010		2.5	262	239.3	1.1
BH-010		4.5	18	31.8	0.6
BH-010A		6.5	11.2	22.5	0.5
BH-011		3.5	238	115.2	2.1
BH-011		9.5	24.8	40.4	0.6
BH-012		5.5	24.3	250.2	0.1
BH-012		9.5	16.3	208.7	0.1
BH-014		4.5	20.2	16.4	1.2
BH-015		5.5	98.8	327.4	0.3
BH-015A		9.5	261.9	744.6	0.4
BH-015A		11.5	6.1	667	0.0
BH-015A		14.5	14	462	0.0
BH-016		7.5	6.3	7.8	0.8
BH-017		3.5	11.5	122.5	0.1
BH-021		2.5	10.4	9	1.2
BH-022		5.5	54.3	9.3	5.8
BH-026		4.5	24.9	21.9	1.1
BH-026		12.5	6.8	8.5	0.8
BH-031		10.5	9.7	26.5	0.4
BH-032		2	6.6	6.3	1.0
BH-034		3.5	6.3	6.9	0.9
BH-038		1	138.6	16.7	8.3
BH-039		1.5	23.3	21.1	1.1
BH-039		8.5	7.7	5	1.5
BH-041		3.5	61.5	5.9	10.4
BH-042		1	32	5	6.4
BH-042		11	9.7	5.3	1.8
BH-051		13.5	8.3	7.9	1.1
BH-052		4	29.4	1511	0.0
BH-053		2	7	9.8	0.7
BH-054		1.5	25.2	192	0.1
BH-055		15	9.6	60.7	0.2
BH-069	0.5	1	5.91	5.05	1.2
BH-086	6	7.5	11.4	7.1	1.6
BH-090	12	13.5	9.7	11.1	0.9
BH-091	12	13.5	28	24.3	1.2
BH-092	12	13.5	10.8	5.36	2.0
BH-112	0	2	11.5	6.06	1.9
BH-114	2	4	30.43	5.6	5.4
BH-121	0	1	6.73	82.51	0.1

ATTACHMENT C

RESRAD Cases

Pertinent RESRAD cases that are the bases of this report are provided in electronic form as RESRAD input and output files.

Revised C-T Phase II Decommissioning Plan
section 14.4.3.7 Surveys

March 20, 2006

judgment will not be included with the data points from the random-start triangular or square grid for statistical evaluations because they are not unbiased, as is assumed in the statistical analysis. These measurements will be compared to the investigation levels described in section 14.4.3.8. Characterization and or remediation survey data may serve this purpose provided they are of acceptable quality.

14.4.3.7 Surveys

After the number of required measurements or samples has been established and the location of the measurements or samples is determined, a survey strategy will be developed using the following guidelines. Final status survey of pavement and of soil will be done separately. Both scans and stationary measurements will be performed for pavement and building slabs. Pavement and building slabs will be surveyed by scans and stationary measurements for beta radiation or conservatively, $\beta + \gamma$. Subsurface materials will be subject to stationary measurements, but not scan surveys.

Class 1 Areas. Scans will be performed over 100% of pavement and building slab surfaces. Locations of radioactive material concentration above the scanning survey investigation level will be identified and evaluated. Stationary location measurements of radioactive material areal density will be performed on pavement at locations identified by scans and at previously determined stationary measurement locations selected to test compliance with $DCGL_W$ and $DCGL_{EMC}$, as described above in Sections 14.4.3.5. Average concentrations of radionuclides in subsurface materials over 1-m vertical increments (averaged 0-to-1 m, 0-to-2 m, 0-to-3 m, *etc.*, down to and including the sampling cutoff layer specified in §14.4.3.5) will be determined at predetermined borehole locations to test compliance with $DCGL_W$. Locations of radioactive material areal density or concentrations above the stationary measurement investigation level will be identified and evaluated. Results of initial and follow-up direct measurements and sampling at these locations where measurements exceed investigation levels will be recorded and documented in the Final Status Survey Report. Temporary pavement was applied following the completion of Phase I Plan work in some Class 1 pavement and slab areas. Prior to the FSS, this temporary pavement will be removed from areas subject to survey to permit accurate survey of the pavement and slab surfaces of interest.

Class 2 Areas. Scans will be performed on at least 10% of pavement and building slab surfaces. Locations of radioactive material concentration above the scanning survey investigation level will be identified and evaluated. Stationary location measurements of radioactive material areal density will be performed at pavement locations identified by scans and at previously determined stationary measurement locations selected to test compliance with $DCGL_W$, as described above in Sections 14.4.3.5. Average concentrations of radionuclides in subsurface materials over 1-m vertical increments (averaged 0-to-1 m, 0-to-2 m, 0-to-3 m, *etc.*, down to and including the sampling cutoff layer specified in §14.4.3.5) will be determined at predetermined borehole locations to test compliance with $DCGL_W$. Locations of radioactive material concentrations above the stationary measurement investigation level will be identified and evaluated. Results of initial and follow-up direct measurements and sampling at these locations where measurements exceed investigation levels will be recorded and documented in the Final Status Survey Report. Temporary pavement was applied following the completion of Phase I Plan work in some Class 2 pavement and slab areas. Prior to the FSS, this temporary pavement will be removed from areas subject to survey to permit accurate survey of the pavement and slab surfaces of interest.

Class 3 Areas. Scans of surfaces will be performed at locations judged most likely to be contaminated as determined through the use of historical knowledge and contractor experience. Locations of direct radiation above the scanning survey investigation level will be identified and evaluated. Stationary measurements of radioactive material concentration will be performed at locations identified by the scans and locations selected to test whether concentrations exceed more than a small fraction of $DCGL_W$. Average concentrations of radionuclides in subsurface materials over 1-m vertical increments (averaged 0-to-1 m, 0-to-2 m, 0-to-3 m, *etc.*, down to and including the sampling cutoff layer specified in §14.4.3.5) will be determined at predetermined borehole locations to test whether concentrations exceed more than a small fraction of $DCGL_W$.

Pavement.[1] In revised CT 2 DP, §5.9.1 $DCGL_W$ on Pavement, $DCGL_W$ on pavement is presented in units, dis/(min· 100 cm^2), and units, β/(min· 100 cm^2) and the basis of derivation is explained. Measurement by beta-ray detection at pavement surface will be as described in C-T Phase I Decommissioning Plan (CT 1 DP), Appendix D, §3 Beta Radiation Measurement, as was approved for and applied to building surfaces. Calibration of beta ray-detecting survey instrumentation is described in CT 1 DP, Attachment 3 Energy Dependent Calibrations for the Bicron Model AB-100 Beta Ray Survey Probe. [also ref. CT 2 DP §14.4.1, incl. Table 14-1]. Scanning pavement will be done with a beta-detecting floor monitor or equivalent. [ref. CT 2 DP §14.4.1, incl. Table 14-1]

Survey methodology is described in CT 2 DP, §14.4.3 Survey Methodology.

Foundations. Above-grade, exposed portions of a foundation are subject to the DCGL that is applicable to pavement and will be subject to final status survey. In the event the exposed portion of a foundation or adjacent portion of a slab in contact with it were contaminated above DCGL applicable to pavement, Mallinckrodt would investigate the possibly affected part of the foundation below grade. A foundation may be surveyed either by direct measurement or by collecting sample(s) of concrete from the foundation surface, *e.g.*, by scabbling, scraping, or chipping. Residual source in that kind of sample would be measured, interpreted as areal contamination, and compared with the areal DCGL applicable to pavement.

A subsurface building foundation within a soil survey unit that requires remedial action adjacent the foundation and exposes it will be subject to measurement of

[1] Direct measurements and analyses of scabble samples from the characterization studies indicate that almost all of the pavement of Plant 5 may be released for unrestricted use. Specifically, Table 4-3 reveals that only 3 of the 1670 measurement results exceeded the proposed release limit; i.e. exceeded the derived concentration guideline level described in Section 5. Additionally, Table 4-2 reveals that only one pavement sample exceeded the exempt concentration limit for release of source material of 0.05% weight, described in 10 CFR 40.13(a). [ref. CT 2DP §4.8.3]

radionuclide concentration in scabble samples from locations selected based on professional judgment. Results of those samples will be considered investigative or remedial action support survey data and will be evaluated to determine whether remedial action for the building foundation is necessary.

Soil. In revised CT 2 DP, §5.8.5 Composite Dose Factors and $DCGL_W$ and in §5.8.6 Compliance Model for Soil, $DCGL_W$ of the radionuclide groups is presented in units, pCi/g soil, and an equation for combining into a sum-of-fractions of $DCGL_W$, or composite index, is included.

Wherever the cinder-fill soil is covered by pavement, measurement of source radionuclides in the soil will begin at the pavement-soil interface. Measurement will be made by soil core sampling and analysis of each core sample by gamma spectrometry. Alternatively, a borehole may be augered and analysis done in-situ by gamma spectrometry. In-ground analysis is described in CT 2 DP, Appendix F, Radionuclide Analysis in Soil by In-ground Gamma Spectrometry.

Soil survey design and performance is described in CT 2 DP, §14.4.3 Survey Methodology.

Clarification of Response to Certain NRC Requests for Additional Information about the C-T Phase II Decommissioning Plan

As noted in the NRC report of a meeting[1] between Mallinckrodt and NRC staff concerning radiological dose modeling pertaining to C-T Phase II Decommissioning, the NRC staff wants additional clarification in response to certain of its Requests for Additional Information. It also wants additional clarification of plans for final status survey of pavement and of soil beneath pavement. These interests are addressed in the following text.

RAI 41, 43, 44, 45, 49, 51, 4 AND 48

RAI 41.

(a) The thickness of the contaminated zone: The licensee selected a thickness of 2 m (RESRAD default value) to represent the contaminated area across the site. However, borehole data showed that the thickness varies from 0.01 to 4.5 m. Albeit that the average thickness may correspond to 2 m; this parameter could be better represented as variable with a distribution between these two limits. Alternatively, the licensee may conduct a sensitivity analysis to demonstrate that a source thickness of more than 2m will not have any significant influence on the dose result.

Response:

An analysis of the effect of contaminated zone thickness on radiological dose during industrial land use has been performed. It interprets the depth beyond which additional contribution from a representative source in soil to irradiation dose to a person becomes negligible. Essential features of modeling to perform this analysis were:

- a reasonably representative source ratio of 3 U series, 0.0455 x 3 actinium (U^{235}) series, and 1 Th series together. (Total source concentration at this ratio was entered into RESRAD to produce a baseline radiological dose rate = 25 mrem/yr at infinite source thickness.);
- bare land in which residual source contamination extends from land surface downward into the soil;
- indoor time fraction = 0.0 in order to simulate effect of irradiation on bare land;
- the same industrial land use scenario modeled to derive $DCGL_W$ originally, except absent ingestion of soil and inhalation of dust; (for the origin of inadvertently ingested dust and of dust suspended into air is surficial topsoil); and
- deterministic simulation using RESRAD to derive the effect of increasing contamination depth in soil on exposure to direct irradiation.

The result of this analysis is summarized graphically in Figure 41. It determined that, in representative simulation, maximum dose rate by direct irradiation is reached asymptotically as the depth of the contaminated zone in topsoil reaches about 30 cm. Additional source thickness would not produce significantly greater dose rate.

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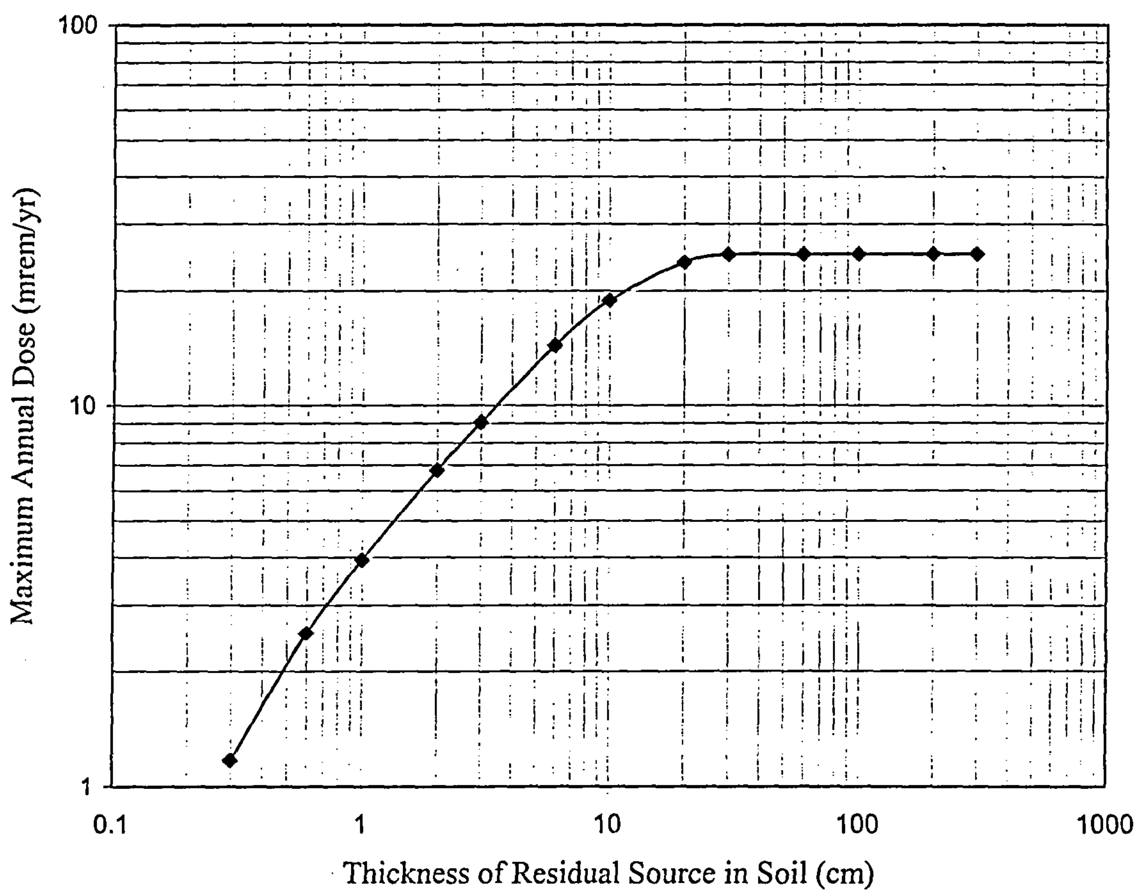
[1] Amir Kouhestani, NRC, letter to Jim Grant, Mallinckrodt, Feb. 16, 2006, with attached meeting report.

This evaluation of the merit of our original modeling representing source thickness has demonstrated that the original basis of 2 meters source depth was exceedingly conservative in modeling dose and deriving DCGL. Nevertheless, we will represent the thickness of contaminated zone parameter as a variable in probabilistic modeling. It is being represented as a uniform distribution ranging from 0 to 1 meter thick. It is being represented as a uniform distribution because characterization survey soil sampling intervals are insufficient to resolve a well-defined gradient within this range. A maximum depth of 1 meter is more than sufficient to be a conservative representation insofar as direct irradiation is concerned.

Figure 41. Maximum Annual Radiological Dose Versus Source Depth in Soil
(infinitely-thick source ratio 3 U series + 1 Th series produces 25 mrem/yr)



RAI 43

(c) The licensee selected an indoor gamma shielding factor of 0.17. In other words the licensee assumed that only 17% of outdoor gamma radiation can be penetrated indoors. The RESRAD default value is 0.7. The licensee indicated that Plant 5 has concrete slab floors or concrete walls with few windows. Therefore, the licensee assumed that the factor 0.17

should represent the gamma shielding for the building flooring and walls. It should be noted that the performance period for decommissioning is1000 years. Therefore, the assumption that concrete floors and walls will be always available and well maintained to shield from gamma radiation is unrealistic. For example, prefabricated buildings may be constructed on the contaminated soil with minimum shielding from walls and floors. Further, a security guard may be located at the entrance of the building with much less shielding from outdoor gamma radiation. It should be noted that the shielding factor for the construction worker was conservatively selected as 1.0; however, the shielding factor for the industrial worker scenario is not well justified. This important sensitive parameter could be better represented as variable with a distribution between the two limits 0.17 and 0.7. Alternatively, the licensee may select a more conservative value for the shielding factor to bound potential site-specific conditions within the 1000 year performance period.

Response:

DCGL have been revised to include the effect of probabilistic distribution of indoor gamma shielding factor.

The floor and walls of a building shield an occupant against some gamma rays entering from soil outside. Buildings in Plant 5 have concrete slab floors and brick or concrete block walls with few windows.

An analysis of the effect of radiation attenuation by a building, especially floor thickness, on radiological dose for the portion of time a worker spends indoors during industrial occupation has been performed. Occupancy 20% of the time on bare ground, with gamma shielding factor = 1.0, is, in addition, assumed to apply deterministically while out-of-doors, even though most of Plant 5 is paved. Overall, then, dose modeling has been adjusted to simulate a person on bare ground about 24% of their time while on-site and thin shielding an additional 5.6% of the time. This is illustrated diagrammatically in Figure 43 A. (same as CT 2 DP Appendix C, Attachment A, Figure C3.)

The gamma shielding factor indoors has been revised to treat it probabilistically and to assume a fractional occurrence on bare ground and a thin floor. Table 43-1 (same as CT 2DP Table 5-2) describes the discrete cumulative probability distribution simulating the external gamma shielding factor that is applicable indoors.

Essential features of modeling to perform this analysis were:

- a reasonably representative source ratio of 3 U series, 0.0455 x 3 actinide (U^{235}) series, and 1 Th series together;
- residual source contamination extends from land surface downward one meter into the soil;
- outdoor time fraction = 0.0 in order to simulate effect of irradiation indoors;
- the same industrial land use scenario modeled to derive $DCGL_W$ originally, except absent ingestion of soil and inhalation of dust;
- deterministic simulation using RESRAD to derive the fraction of gamma dose rate as a function of concrete floor thickness (ref. Figure 43b); and
- combination of probable distribution of floor thickness and indoor gamma shielding factor to derive a probability distribution of indoor gamma shielding factor.

Figure 43A. Cumulative Distribution of Indoor and Outdoor Shielding Fraction

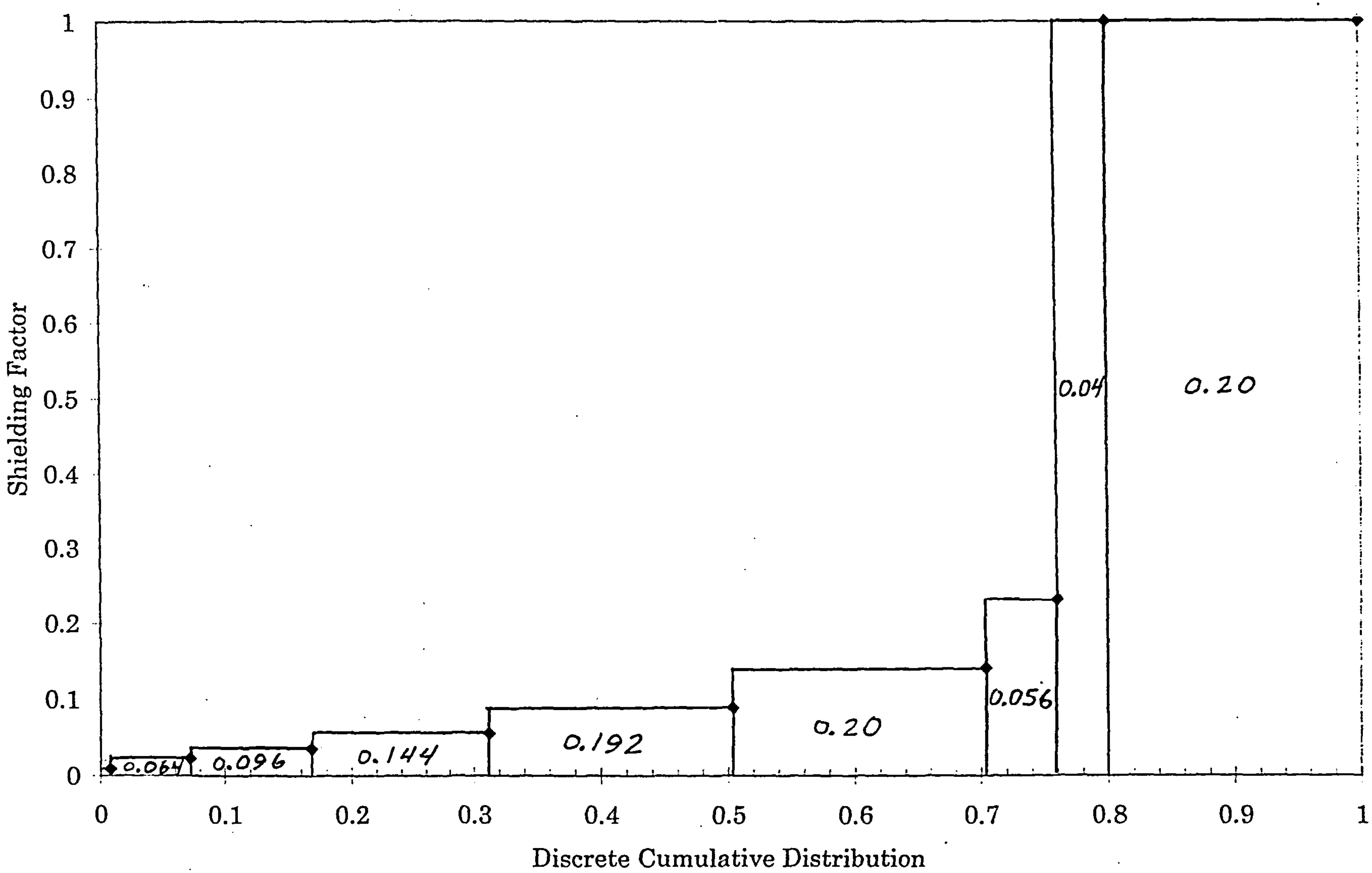
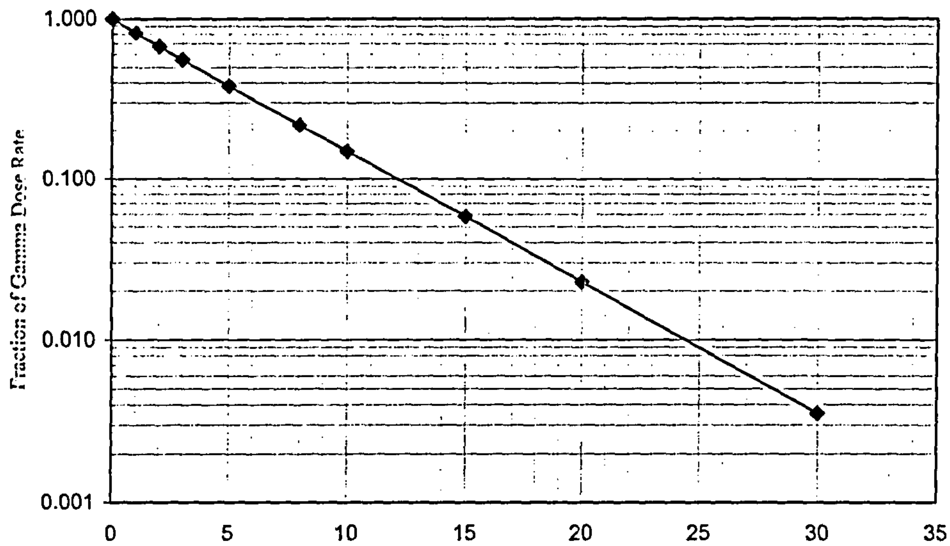


Figure 43 B. Fraction of Gamma Dose Rate Penetrating a Concrete Floor
source ratio: 3 U series + 0.1365 U235 series + 1 Th series; one meter deep in soil



The result of this modeling is summarized in Table 43-1 (same as CT 2 DP, §5, Table 5-2) where indoor gamma shielding factor probability distribution is tabulated.

Table 43-1. Indoor Gamma Shielding Factor Distribution

Shielding Thickness (cm)	(in)	Shielding Factor ("value")	Fractional Occurrence	Cumulative Distribution Indoor Only (cdf)
25.4	10	0.0084	0.01	0.01
20.3	8	0.022	0.08	0.09
17.8	7	0.035	0.12	0.21
15.2	6	0.055	0.18	0.39
12.7	5	0.088	0.24	0.63
10.2	4	0.14	0.25	0.88
7.6	3	0.23	0.07	0.95
0	0	1.0	0.05	1.0

Table 43-1 is the same as CT 2 DP §5, Table 5-2 and CT 2 DP Appendix C, Attachment A.

While dose analyses would still be projected for 1000 years, recent NRC staff view is to allow justification of scenarios based on the reasonably foreseeable future instead of any viable land use envisioned during the next 1000 years.[2] The "reasonably foreseeable future"

[2] NRC. "Results of the License Termination Rule Analysis." SECY-03-0069. May 2, 2003.

would be based on what land uses are likely within a time period of the next few decades to about a hundred years. Industrial buildings have a finite, useful lifetime and are assumed to be replaced in kind instead of assuming maintenance for 1000 years. Physical and geological characteristics of the cinder fill and current and past engineering practice have caused Mallinckrodt to construct concrete slab on grade floors in its buildings. While alternate construction is conceivable, concrete slab flooring is and will continue to be what is reasonably foreseeable in industry. An estimate of the most likely distribution of concrete slab floor thickness in the foreseeable future is in Table 43-1.

On the premise that a floor construction is likely to be specified in an integer thickness in units of inches, a *discrete cumulative* probability distribution of the variable, *external gamma shielding factor*, during indoor occupancy has been specified in RESRAD. Table 43-1 depicts the cumulative probability and indoor gamma shielding factor data entered into RESRAD for probabilistic evaluation of the effect of this parameter on radiological dose rate. RESRAD modeling estimates the time of peak exposure occurs now or in the near future.

A relevant association is that, on the area of the site that is subject to the FUSRAP, the USACE remediation and dose modeling are based on a premise that the land will be covered by at least six inches of pavement, gravel, or unaffected fill.

RAI 44.

(d) The Occupancy Time: The licensee selected for the industrial worker scenario an occupancy time of 0.1825 for indoors and 0.04566 for outdoors. These factors should be acceptable because they are based on an estimated 2000 working hours per year. The occupancy time for the construction worker scenario, however, was selected based on 80 working hours per year corresponding to a time fraction of 0.0081 expended outdoors. The 80 hours occupancy time may be limited to a certain construction worker doing excavation at the site. However, construction workers may conduct other activities besides excavation and may perform renovation activities. NUREG/CR-5512 Vol. 1 considered an occupancy time for building renovation of 8 h/d , for a total exposure period of 90 days. This time period corresponds to 28.3 days on the job which is equivalent to 0.057 time fraction for the year. However, for this scenario a fraction of this time should be expended indoors. Therefore, the occupancy time fraction for the construction worker scenario may be considered in two parts, an outdoor time fraction of 0.0081 and an indoor time fraction of 0.041. Because this parameter is uncertain, a distribution of occupancy parameter for outdoor could be represented in the range 0.008 - 0.041 and for the indoor in the range of 0.0 - 0.041. If the licensee prefers to exclude this scenario from the analysis and preferably use conservative assumptions and parameters for the industrial worker scenario this issue may be disregarded.

Response:

$DCGL_W$ and $DCGL_{EMC}$ applicable to soil are based on the industrial worker scenario, which is more constraining than the construction worker scenario. The construction worker scenario was evaluated and described for completeness.

This staff comment indicates that industrial occupancy time fractions of 0.1825 indoors and 0.04566 out-of-doors should be acceptable inasmuch as they combine to the equivalent of a 2000-hour work-year. We would propose to retain these single-valued estimates in dose modeling. They are not likely to underestimate the occupancy time of an industrial worker in Plant 5. For by comparison, the USACE estimated industrial worker occupancy 0.1969 of time indoors and 0.04566 out-of-doors on nearby Plant 2;[3] while the ANL staff estimated industrial worker occupancy indoors to be 0.17 of the time and occupancy out-of-doors to be 0.06 of the time.[4]

Industrial worker occupancy is prominently greater than that of a construction or utility worker, especially since outdoor construction or utility work is likely to be done intermittently by contract labor. In view of less occupancy in the construction work scenario, and in view of commentary in this RAI, the construction, or utility, work scenario in CT Phase II Decommissioning Plan, §5.8.2 is being omitted from further consideration.

RAI 45

(e)Derivation of radionuclide specific $DCGL_w$ based on the radionuclide Guideline (G(i,t) at the time of the total peak dose. The licensee presented the $DCGL_w$ for each specific radionuclide (Table 5-1, page 5-3) based on the guidelines (e.g., radionuclide concentration equivalent to 25 mrem/y) at the time of the peak dose($G(i,t_{peak})$ of the overall radionuclides in the three decay series. This approach is no-conservative and contrary to the recommendation of NRC Guidance in NUREG-1757, Vol. 2, Section 2.7. When using the sum-of-fraction approach to establish the radionuclide specific DCGLs the licensee should select the conservative radiuonuclide specific guideline limit at the minimum single radionuclide soil guideline (G $(i,t_{min}$). Therefore, using NUREG-1757, Vol. 2 recommendations, the radionuclide specific DCGLs would change significantly. For example, The Th-232 DCGL using the $G(i,t_{peak})$ was derived at 394.9 pCi/g, whereas the Th-232 DCGL using the G $(i,t_{min}$) would be 20.77 pCi/g. The licensee should explain further and justify selection of these radionuclide specific DCGLs assuming that the sum-of-fraction principle would be applied. Alternatively, the licensee may clarify that the radionuclide sum-of-fraction approach will not be used in the demonstration of compliance with the dose criteria.

Response:

In response to NRC staff suggestions concerning dose modeling, Mallinckrodt derived radiological dose factors and DCGL for soil probabilistically with the aid of RESRAD. The probabilistic derivation of dose factors and $DCGL_W$ applicable to soil is explained in revised Appendix C. Values of parameters that are site-specific or sensitive are described in CT 2 DP, revised §5 Dose Modeling, and in Appendix C. In its analysis and description, Mallinckrodt:

- Treated three parameters probabilistically
  - Airborne dust loading

3 USACE. Post-Remedial Action Report for the St. Louis Downtown Site Plant 2 Property. Table B-3. June 2001.

4 Yu, C., *et. al.*, ANL/EAD-4, Table 2-3, p. 2-22.

- Depth of contaminated soil in ground, and
- Indoor gamma shielding factor, as a function of concrete floor thickness.

- Evaluated the sensitivity of radiological dose as a function of Th^{230} concentration in soil.
- Accounted for effects of Th^{230} and Ra^{226} in dose factors and DCGL.
- Stated DCGL and sum-of-fractions simply and clearly in revised CT 2 DP, §5.
- Derived area factors probabilistically and compatibly with the $DCGL_W$; and
- Clarified statement of $DCGL_W$ and area factors for $DCGL_{EMC}$ on pavement

- Radionuclides were grouped logically when deriving dose factors and DCGL for the ores processed in C-T
  - Natural uranium, including U^{238}, U^{234}, U^{235} series, and their short-lived progeny
  - Th^{230}, Ra^{226}, Pb^{210}, and their short-lived progeny
  - Th^{232}, Ra^{228}, Th^{228}, and their short-lived progeny
- Derivation of DCGL compensated for the range of Th^{230} relative to Ra^{226} by assuming Th^{230} to be 6 times the concentration of Ra^{226} when deriving a composite dose factor and DCGL
- Th^{230} is associated with Ra^{226}, its immediate progeny. Measurement will rely on Ra^{226} as an indicator, or surrogate, of Th^{230}.

Mallinckrodt believes that the approach used to calculate the $DCGL_Ws$ is consistent with NRC guidance[5], is not non-conservative, and does meet the requirements of 10 CFR Part 20, Subpart E. Statements in NRC guidance[6] indicate that site specific analysis using realistic dose modeling can be used to calculate DCGLs. Mallinckrodt is confident that it has sufficient site characterization survey data and has done sufficient dose modeling in an approach that is consistent with guidance in NUREG-1757 to demonstrate that the DCGL proposed in CT 2 DP §5, Table 5-1, meet the intent and requirements of NUREG-1757.

RAI 49.

(i) Area Factor for Elevated Measurements: The licensee calculated the area factor for the industrial scenario elevated measurements exposure to soil and to pavement. The area factor is the ratio of the composite dose factor for the survey unit area to the composite dose factor for the local area (e.g., elevated measurements) of contamination. The licensee calculated the area factor for elevated measurements criterion in soil using contaminated areas of 10, 30, 100, 200, 1000, and 2000. A survey unit area of 10,000 m^2 was used for derivation of the area factor. In summary the area factor varied in the range of 1.1 (for an elevated area of 1000 m^2) to 2.3 for an elevated area of 10 m^2 for the composite radionuclide source of U-series , Ac-series, and Th-series. Similarly, the licensee calculated the area factors for elevated measurements on pavements for areas ranging from 10 m^2 to 2000m^2. These factors were found to vary in the range of 5.5 for the 10 m^2 area to 1.2 for the 2000m^2 area. The comments provided above regarding derivation of the $DCGL_w$ would also be applicable to derivation of the elevated measurements using the area factor (*e.g.*, the $DCGL_{EMC}$).

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5 NRC. Consolidated NMSS Decommissioning Guidance. NUREG-1757, 2, §2.7.
6 NRC. NUREG-1757, 2, §2.5.2.

Response:

Area factors for elevated measurements with respect to contaminated soil and to pavement are presented in CT 2 DP, revised §5, Figures 5-3 and 5-4 respectively. Derivation of $DCGL_W$ for soil and $DCGL_W$ for pavement have been estimated probabilistically as revised to resolve NRC comments concerning derivation of $DCGL_W$. Since $DCGL_W$ in the equation, $DCGL_{EMC}$ = Area factor x $DCGL_W$, were revised, the corresponding simulations as a function of diminishing area have also been revised. The same dose modeling, varying only the assumed contaminated area, was employed to derived the area factors and $DCGL_{EMC}$ in soil and on pavement.

Soil. Table 5-1 in original CT 2 DP is being replaced by revised Table 5-3. It becomes the basis for revised derivation of $DCGL_{EMC}$ to replace original CT 2 DP Figure 5-1, "Area Factors for Elevated Measurements Criterion for Soil." Revised area factors applicable to soil appear in revised CT 2 DP §5, Figure 5-3, "Area Factors for Elevated Measurements Criterion in Soil."

Pavement. RAI item 48, Table 48-2 becomes the basis for revised derivation of $DCGL_W$ on pavement. $DCGL_W$ on pavement in original CT 2 DP Table 5-3 is thereby being replaced by Table 5-4, "Uranium Series and Thorium Series Limits on Pavement Producing 21.2 mrem/yr After Reduction for Gamma Radiation from Soil."

The same dose modeling, varying only the assumed contaminated area, was employed to derived the area factors and $DCGL_{EMC}$ on pavement. On that basis, original CT 2 DP Figure 5-2, "Area Factors for Elevated Measurements Criterion for Pavement." is replaced by revised area factors appearing in revised §5, Figure 5-4, "Area Factor for Elevated Measurement on Pavement."

RAI 51.

A. Identify all contaminated areas on site, to include former burials and potential in-accessible contamination, so that NRC staff can determine how to precede with its Environmental Assessment under 10 CFR Parts 51.21, 51.30, and 51.45:

1. Identify all areas (structures, systems, equipment and matrices) of the Mallinckrodt site that are contaminated or potentially contaminated. Provide radiological and non-radiological characterization data. Identify potential remediation strategies and potential waste volumes for each media/matrix so that NRC staff can evaluate all potential impacts under the National Environmental Policy Act (NEPA).
2. Identify whether any offsite contamination (attributable to Mallinckrodt operations) was found and/or cleaned-up on the properties adjacent to the Mallinckrodt site
3. Identify any contaminated utilities, such as sewerage lines, that extend beyond the site boundary or extend to the levee.

Response:

It was Mallinckrodt's intention that the DP would answer most of the questions noted in the DP. These topics are essentially covered in sections 4 and 8 of the draft DP. Table 51 below summarizes and cross references some of this information. Radioactive material characterization data are in CT 2 DP §4 "Radiological Status of Facility." Mallinckrodt does not anticipate generating any mixed-waste.

Location of the URO burials can be found in Figure 2-5 in the draft DP.

Mallinckrodt does not believe there are any inaccessible areas contaminated by C-T residues. Figure 2-5 shows that Burial site 10 is located under the floor of an existing warehouse, but this burial will be remediated along with the other burials. Figure 4-17 indicates contamination adjacent to Building 240, but Mallinckrodt believes this is due to a sewer located in this area and that contaminated soil will be accessible.

Section 2.4.2 of the DP discusses the MED/AEC operations that occurred at the site during the 1940s and 1950s, and the FUSRAP remediation being implemented at the site by U. S. Army Corps of Engineers (USACE). There was significant MED/AEC processing in much of the plant outside of Plant 5 as shown in DP Figure 2-3. Significant remediation has been done in Plants 1, 2 and 10. USACE is now remediating Plants 6 and 7.

The USACE has done a comprehensive survey of vicinity properties and is doing characterization and remediation as required. Additional information is provided in response to item 64 herein.

Sections 8.4.1 and 8.4.6 discuss sewerage related to the MED/AEC operations, and Section 8.4.1 mentions the sewer line that passed through the Plant 6/7 area.

Table 51. Potentially Contaminated C-T Areas

Item	Location	Reference to Decommission Plan	Remediation Strategy	Waste Volume Estimate (ft^3)
Plant 5 pavement	DP Fig. 14-1A	CT 2 DP §4.8.3	Decontamination or removal and disposal off-site.	4100.
Plant 5 building slabs		CT 2 DP §4.8.3	Decontamination or removal and disposal off-site.	13000.
Plant 5 soil and subsurface material	DP Figs. 4-17,18,19	CT 2 DP §4.8.4	Excavation and disposal off-site.	42000.
Sewerage from Plant 5 to wastewater basins	DP Fig. 4-1	CT 2 DP §4.8.2	Expected to meet release criteria. Else, removal and disposal of sediment or removal of sewerage and disposal of debris.	0
Wastewater lift station	DP Fig. 4-5	CT 2 DP §4	Expected to meet release criteria. Else, decontamination, with waste disposal off-site	0
Wastewater Neutralization Basins in Plant 7W	DP Fig. 4-5	CT 2 DP §4	Expected to meet release criteria. Else, decontamination, with waste disposal off-site	0
URO buried in Plant 6W	DP Fig. 2-5	CT 2 DP §2.6	Excavation and disposal off-site	81500

SUPPLEMENTAL DESCRIPTION OF FINAL STATUS SURVEY METHODS

During a meeting on January 24, 2006, NRC staff requested additional description of methods of final status survey of pavement and of soil beneath pavement. Final status survey of pavement and of soil will be done separately.

Pavement.[7] In revised CT 2 DP, §5.9.1 $DCGL_W$ on Pavement, $DCGL_W$ on pavement is presented in units, dis/(min· 100 cm^2), and units, β/(min· 100 cm^2) and the basis of derivation is explained therein. Measurement by beta-ray detection at pavement surface will be as described in C-T Phase I Decommissioning Plan (CT 1 DP), Appendix D, §3 Beta Radiation Measurement, as was approved for and applied to building surfaces. Calibration of beta ray-detecting survey instrumentation is described in CT 1 DP, Attachment 3 Energy Dependent Calibrations for the Bicron Model AB-100 Beta Ray Survey Probe. [also ref. CT 2 DP §14.4.1, incl. Table 14-1]. Scanning pavement will be done with a beta-detecting floor monitor. [ref. CT 2 DP §14.4.1, incl. Table 14-1]

Survey methodology is described in CT 2 DP, §14.4.3 Survey Methodology.

Soil. In revised CT 2 DP, §5.8.5 Composite Dose Factors and $DCGL_W$ and in §5.8.6 Compliance Model for Soil, $DCGL_W$ of the radionuclide groups is presented in units, pCi/g soil, and an equation for combining into a sum-of-fractions of $DCGL_W$, or composite index, is included.

Wherever the cinder-fill soil is covered by pavement, measurement of source radionuclides in the soil will begin at the pavement-soil interface. Measurement will be made by soil core sampling and analysis of each 1-meter interval of core sample by gamma spectrometry. Alternatively, a borehole may be augered and analysis done in-situ by gamma spectrometry. In-ground analysis is described in CT 2 DP, Appendix F, Radionuclide Analysis in Soil by In-ground Gamma Spectrometry.

Soil survey design and performance is described in CT 2 DP, §14.4.3 Survey Methodology.

Responses to RAI set 1, items 4 and 48, are also informative.

RAI 4.

Chapter 5: Please clarify if the soil and pavement scenarios are independent, *i.e.*, if exposures to pavement/slabs and soil are mutually exclusive.

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[7] Direct measurements and analyses of scabble samples from the characterization studies indicate that almost all of the pavement of Plant 5 may be released for unrestricted use. Specifically, Table 4-3 reveals that only 3 of the 1670 measurement results exceeded the proposed release limit; i.e. exceeded the derived concentration guideline level described in Section 5. Additionally, Table 4-2 reveals that only one pavement sample exceeded the exempt concentration limit for release of source material of 0.05% weight, described in 10 CFR 40.13(a). [ref. CT 2DP §4.8.3]

Response:

The scenario of exposure to bare soil, on which DCGL for soil were derived, and the scenario of exposure to pavement, on which DCGL for pavement were derived, cannot occur simultaneously.

Exposure to bare soil and to pavement cannot occur simultaneously. The scenario assuming bare soil necessarily excludes pavement and any exposure to it. Without pavement, exposure pathways to pavement are absent. Thus, DCGL derived for soil are independent of presence of or contribution from pavement.

On the other hand, pavement and its crushed stone base would exist atop soil. When so, it would be a complete barrier against airborne and ingestion pathways of exposure to conceivable residue in the soil and an incomplete shield against gamma radiation penetrating from conceivable residue in the soil. With the aid of dose modeling of outdoor exposure to gamma radiation penetrating nominal 4-inch-thick pavement by RESRAD, one finds that 2 meters of soil containing $DCGL_W$ concentration of 3 U-to-1 Th series source would be estimated to contribute 3.8 mrem/yr through the pavement. Subtracting that from 25 mrem/yr allotted to DCGL would imply reduction of conceivable contribution from residue on pavement itself to 0.85 of the $DCGL_W$ derived for pavement and would eliminate question of allocation of maximum acceptable total dose.

Although it is unlikely that both soil and pavement would be contaminated to more than 0.85 of either $DCGL_W$, and thus are practically independent, $DCGL_W$ on pavement in CT 2 DP §5, Table 5-3, is being reduced by 0.15.[8] Together with revisions in response to item 48, values in Table 48-2 herein become the revised $DCGL_W$ to be applied. As a consequence $DCGL_{EMC}$ will also be reduced to nominally 0.85 of currently proposed values in Figure 5-2 (now identified as Table 5-4).

RAI 48.

(h) Assumptions for the Industrial Worker Exposure to Pavement: For the exposure of industrial worker to residual radioactivity on pavements, the licensee made similar assumptions as those for the soil. However, the licensee assumed a thin layer of surface contamination on pavement with thickness of 0.1 cm. The licensee modified the approach to convert volumetric dose analysis results into surface activity results (e.g., dpm/100 cm^2). This was done through derivation of the radionuclide volumetric dose factor (mrem/y per pCi/g), converting this factor into areal density factor pCi/100 cm^2 (e.g., by assuming a thickness of pavement of 0.1 cm and a density of 1.5 g/cm^3) corresponding to 25 mrem/y and then converting the pCi into dpm (e.g., by multiplying by 2.22). Therefore, considering the volumetric dose analysis approach the following parameters and assumptions were made for industrial worker exposure to the pavement source: (i) Contaminated Zone: the

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[8] Existing Table 5-3, concerning $DCGL_W$ in soil of a construction scenario, is being omitted. Existing Table 5-3, concerning $DCGL_W$ on pavement, will be renumbered to become Table 5-2.

licensee assumed that 0.1 cm thickness of soil adequately represents areal contamination on pavement. This is less conservative than the 2 m thickness assumed for the exposure to soil; (ii)The erosion rate for the pavement was assumed to be zero.

The licensee needs to verify that contamination only exist in a pavement medium of 0.1 cm thickness and no contamination below this thin crust of the pavement. In addition, by assuming an erosion rate of zero the licensee assumed that the pavement would be maintained through a performance period of 1000 years. The licensee needs to verify these assumptions and provide data and a rationale that the thin pavement layer would be maintained over a 1000 year time-frame.

Response:

Modeling Exposure. In the outdoor environment of interest, the potential exposure pathways would mainly be by direct gamma irradiation, inhalation of dust suspended into air, and ingestion of dust. Among these, the model simulating suspension of dust into outdoor air in RESRAD is appropriate; whereas the indoor ventilation model in RESRAD-BUILD would be less adaptable. The conceptual models for ingestion and inhalation in RESRAD are a function of radioactivity concentration in the surface dust or soil and not on its depth. Consequently, RESRAD was employed because it would be preferable for exposure to an outdoor source on pavement via these pathways.

Compatibility of Areal DCGL on Pavement and Mass DCGL in Soil Beneath. When considering derivation of DCGL, one factor is whether exposure to pavement and to soil beneath are independent. The near independence of exposure to pavement and soil is answered in response to item 4 herein. In essence, the scenario of exposure to bare soil, on which DCGL for soil were derived, and the scenario of exposure to pavement, on which DCGL for pavement were derived, cannot occur simultaneously. Absent pavement, exposure pathways to pavement are absent, and exposure to topsoil can occur. Thus, DCGL derived for soil are independent of presence of or contribution from pavement. Pavement would exist atop soil. When so, it would be a complete barrier against airborne and ingestion pathways of exposure to conceivable residue in the soil and an incomplete shield against gamma radiation penetrating from conceivable residue in the soil beneath. Resolution of item 4 herein also compensates for and effectively uncouples this dependence.

By this logic, it is not essential that pavement be maintained 1000 years without erosion. For if pavement were to erode or be removed, so would source on or embedded in the pavement be removed.

If the inventory corresponding to the areal $DCGL_W$ derived for the surface of pavement were embedded or migrated downward into pavement, the dose would diminish because of internal shielding of gamma radiation by pavement material. The inventory to be allowed on pavement surface corresponding to the areal $DCGL_W$ proposed in Table 5-3 would be less than inventory in about 4 cm of topsoil at the $DCGL_W$ specified in Table 5-1. (Tables now identified as Tables 5-4 and 5-3)

In a nominally representative mixture of 3 U series -to- 1 Th series, the areal density at the $DCGL_W$ on pavement or a building slab is the same as the areal density equivalent of the $DCGL_W$ concentration in 4 cm of soil. In other words, if radioactive source material at the $DCGL_W$ in the top 4 cm of topsoil were concentrated at the surface, the areal density would be the same as the $DCGL_W$ applicable on the surface of pavement or a building slab. In perspective, then, the relation in radioactivity between the $DCGL_W$ derived for application on pavement or a building slab and separately in topsoil is a reasonable one.

Areal DCGL on Pavement or Building Floor Slab. Whereas, a comment seeks justification of 0.1 cm thickness of residual source contamination on pavement, the objective in dose modeling was to determine the maximum **areal density** of contaminant on or near the surface that would not cause more than 25 mrem/yr.

RESRAD models simulate exposure to a source originating as a mass concentration in soil.[9] In order to simulate surficial contamination on pavement out-of-doors, a mass concentration equivalent of areal density of source material on pavement needs to be estimated. Assumption of 0.1 cm source thickness is sufficient for contamination of worker hands or clothing and potential for ingestion and removal from the surface to become suspended in air for potential inhalation. That is, modeling removal for either ingestion or inhalation pathways does not depend on a thicker source.

A common sense perspective on the assumption of 0.1 cm source thickness on pavement in Plant 5 may be realized by estimating the volume it would occupy. That volume would be 30 cubic yards, or three 10-cubic-yard, semi-trailer truck loads. Even if 2/3 of Plant 5 pavement were vacuum-cleaned (the remaining area occupied by structures), it would be quite unrealistic to expect to accumulate as much as two 10-cubic-yard, semi-trailer truck loads of sediment on the pavement remaining from more than 15 years ago.

Another expressed concern is whether contamination might be beneath, or deeper than, the assumed 0.1 cm thick surface contamination. Again, the pertinent objective is to derive the maximum acceptable average areal density, or $DCGL_W$, in units $pCi/100\ cm^2$ or $dis/(min \cdot 100\ cm^2)$ of surficial contamination, regardless of its depth of embedment.

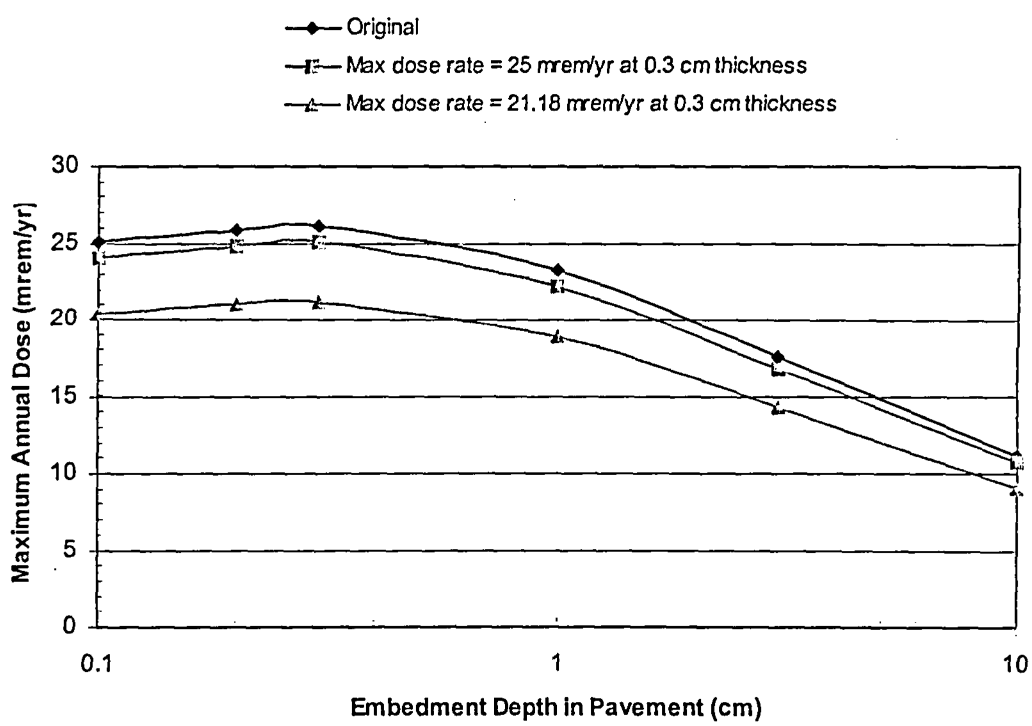
To examine this issue, modeling has been done assuming residual U and Th series as a function of source thickness or embedment into pavement. The objective is to derive the maximum areal density of CT residue **on or embedded in** an outdoor surface, including pavement and CT process building slabs, that would cause no more than 25 mrem/yr. Results have been compared with dose modeling underlying basis Table 5-3 in CT 2 DP §5. Whether concentrating a source on a surface or assuming it is embedded into pavement or a building slab would produce maximum annual dose becomes a central question to be investigated. To do this,

9 Whereas, RESRAD-BUILD simulates indoor contamination with indoor dust suspension and ventilation models. Both are inappropriate for outdoor airborne exposure modeling.

- A reasonable spectrum of radionuclides in CT residue is represented by a ratio of 3 U series + 0.0455 x 3 U^{235} series + 1 Th series in radioactive equilibrium.
- The relative radioactivity fraction in this ratio and the basis dose factor[10] of each key radionuclide are used with a sum-of-fractions expression to derive the areal density and equivalent mass concentration in dust (soil at 1.5 pCi/g density) on pavement surface that would produce 25 mrem/yr.
- Enter this areal density equivalent mass concentration into RESRAD with the same parameter values otherwise used as a basis to derive the areal $DCGL_W$ in CT 2 DP §5, Table 5-3 to verify whether it calculates 25 mrem/yr maximum total dose rate.
- Assume the same radionuclide spectrum at the same areal density were embedded into pavement (represented by 1.5 g/cm^3 soil). Use RESRAD to compute maximum total dose rate as a function of increasing depth of embedment.

A premise of CT 2 DP, §5, Table 5-3 is that an equivalent areal density of CT residue would produce less dose when embedded than when accumulated on the surface; hence the source was originally modeled as concentrated into a 0.1 cm layer on the surface. Unexpectedly, maximum total dose occurs when the source is 0.2 to 0.3 cm thick, or deep, as illustrated in Figure 48, curve "♦ Original."

Figure 48 Refinement of CT 2 DP §5 Model for Pavement



[10] The basis dose factor (mrem/yr)/(pCi/g) on which the areal $DCGL_W$ in CT 2 DP is derived.

This observation prompted derivation of $DCGL_W$ assuming 0.3 cm contaminant thickness of the long-lived radionuclides in the uranium series, the actinium (U^{235}) series, and the thorium series, assuming short-lived nuclides (<180 day half-life) to be in transient radioactive equilibrium with their parent. The revised result appears here in Table 48-1. The result of this refinement is illustrated in Figure 48 by the curve, "■ Max. Dose Rate = 25 mrem/yr at 0.3 cm thickness". Thus, if contamination were on the surface or even if it were unevenly embedded into pavement or a building slab, controlling to a maximum areal density specified in Table 48-1 would assure that maximum annual dose would not exceed 25 mrem/yr.

Table 48-1. Uranium Series and Thorium Series Limits on Pavement Surface
Derivation Basis is 0.3 cm Thick Surficial Source

Radionuclide	Dose Factor	**Areal Density Equal to 25 mrem/yr**	
	(mrem/yr)/(pCi/g)	(pCi/100 sq cm)	(dpm/100 sq cm)
U-238	7.000E-04	1.77E+06	3.93E+06
U-235 +DI	2.018E-02	5.58E+04	1.24E+05
U-234	5.238E-05	2.15E+07	4.77E+07
Th-230	1.561E-04	7.21E+06	1.60E+07
Ra-226	4.825E-02	2.33E+04	5.18E+04
Pb-210	1.269E-03	8.87E+05	1.97E+06
Th-232	1.954E-03	5.76E+05	1.28E+06
Ra-228	1.911E-02	5.89E+04	1.31E+05
Th-228	3.421E-02	3.29E+04	7.30E+04
U-238 +DI	5.128E-02	2.19E+04	4.87E+04
Th-232 +DI	5.527E-02	2.04E+04	4.52E+04

Our response to NRC query expressed in item 4 herein concerning potential irradiation from hypothetical C-T residue in soil beneath pavement, states, in part:

With the aid of dose modeling of outdoor exposure to gamma radiation penetrating nominal 4-inch-thick pavement by RESRAD, one finds that 2 meters of soil containing $DCGL_W$ concentration of 3 U-to-1 Th series source would be estimated to contribute 3.8 mrem/yr through the pavement. Subtracting that from 25 mrem/yr allotted to DCGL would imply reduction of conceivable contribution from residue on pavement itself to 0.85 of the $DCGL_W$ derived for pavement and would eliminate question of allocation of maximum acceptable total dose.

Although it is unlikely that both soil and pavement would be contaminated to more than 0.85 of either $DCGL_W$, and thus are practically independent, $DCGL_W$ on pavement in CT 2 DP §5, Table 5-3, is being reduced by 0.15 to values in Table 48-2 herein, which become the revised $DCGL_W$ to be applied. As a consequence, $DCGL_{EMC}$ will also be reduced to nominally 0.85 of currently proposed values.

Table 48-2. Uranium Series and Thorium Series Limits on Pavement Surface

Radionuclide	Dose Factor (mrem/yr)/(pCi/g)	**Areal Density Equal to 21.2 mrem/yr** (pCi/100 sq cm)	(dpm/100 sq cm)
U-238	7.000E-04	1.36E+06	3.03E+06
U-235 +DI	2.018E-02	4.72E+04	1.05E+05
U-234	5.238E-05	1.82E+07	4.04E+07
Th-230	1.561E-04	6.11E+06	1.36E+07
Ra-226	4.825E-02	1.98E+04	4.39E+04
Pb-210	1.269E-03	7.51E+05	1.67E+06
Th-232	1.954E-03	4.88E+05	1.08E+06
Ra-228	1.911E-02	4.99E+04	1.11E+05
Th-228	3.421E-02	2.79E+04	6.18E+04
U-238 +DI	5.128E-02	1.86E+04	4.13E+04
Th-232 +DI	5.527E-02	1.72E+04	3.83E+04

Figure 48, curve "▲ Max dose rate = 21.18 mrem/yr at 0.3 cm thickness," confirms that the revised $DCGL_W$ in Table 48-2, to become CT 2 DP §5, Table 5-4 (replacing Table 5-3),[11] would constrain maximum potential annual dose from contamination on pavement, even if embedded, to no more than 21.2 mrem/yr.

Erosion of Pavement. The reason for assuming no erosion of pavement was to simulate sustaining the surficial source in order to maximize potential dose. Else, source material on pavement would erode along with the pavement, thereby diminishing the source. Whereas, apparent concern of agency staff about maintenance of pavement for 1000 years seems to imagine it to be needed to shield against gamma irradiation by residue in soil beneath. Consider, however,

- $DCGL_W$ in topsoil was derived assuming bare soil.
- Gamma radiation from residual source in soil beneath pavement would, at its $DCGL_W$, contribute about 3.8 mrem/yr, or 0.15 of 25 mrem/yr, by irradiation through pavement.
- Weathering is likely to remove surficial residue from pavement, or if ever present, has already done so already.
- It is reasonable to expect surficial contamination on outdoor pavement to be removed by weathering more rapidly than erosion of pavement would allow gamma radiation penetrating from beneath it to increase.
- Even if a surficial source initially at its $DCGL_W$ were to migrate into pavement or a slab, it would diminish to the $DCGL_W$ appropriate for soil, specified in CT 2 DP §5, Table 5-1, within about 6 cm depth into the pavement or slab, such that the combined dose rate would be no greater than for soil alone, even as the pavement was eroding.

That the erosion rate of source sediment on pavement is assumed to be zero maintains the source in RESRAD simulation present on the pavement surface indefinitely in order to assess whether maximum dose might be greater in future than

[1] Existing Table 5-2, the $DCGL_W$ for a construction scenario, is being omitted.

near the beginning time of simulation. Since the maximum dose occurs near the beginning time of simulation, the assumption of zero erosion rate of source from pavement surface is otherwise of no practical consequence to the $DCGL_W$ derived with the aid of RESRAD.

If the pavement were to erode, a surficial source would be expected to disappear more readily, or at least would disappear at the rate of erosion of the pavement. That is, as pavement erodes, dose from surficial source, even if embedded into pavement, would diminish more than dose from source in soil beneath would increase. In either prospect, the source inventory per unit area on or in pavement may be as much as allowed by Table 48-2 and the 25 mrem/yr dose criterion would still be satisfied. Another perspective is that **modeling a source on pavement as a thin, surficial source maximizes potential radiological dose per unit areal density**. If the source were embedded into pavement, ease of removal for contamination of worker hands or clothing and potential for ingestion would be diminished. Likewise, ease of removal from the surface to become suspended in air for potential inhalation would be diminished. Furthermore, unlike an embedded source, a surficial source is without shielding by its substrate.